AFML-TDR-64-280
VOLUME II (REVISED 1970)

AD 713620

CRYOGENIC MATERIALS DATA HANDBOOK

VOLUME II

SECTIONS D, E. F, G, H AND I

TECHNICAL DOCUMENTARY REPORT
AFML-TDR-64-280
(REVISED 1970)

JULY 1970

AIR FORCE MATERIALS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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Technical Report ML-TDR-64-280, Revised 1970, supersedes ML-TDR-64-280, Aug 1964 AD-609-562 and its Supplements 1, 2, 3, and 4 - having AD numbers AD-611-165, AD-618-065, AD-633-388, AD-679-087, respectively.

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Osgood, Samuel H.
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13. ABSTRACT

The eight sections of the two volumes of the handbook contain data on various properties of 88 metallic and nonmetallic materials at cryogenic temperatures. In addition to property data, there is information on tests procedures, other sources of cryogenic data, a treatment of nonmetallic materials used in cryogenic service applications, with a bibliography and a "Materials Selection Guide". The handbook and its supplements were developed under several contracts with the Martin Marietta Corporation. This revision is just a compilation of their reports performed at the Air Force Materials Laboratory.

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Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cryogenic						
Metallic						
Non-metallic						
Materials						
Properties						

AFML-TDR-64-280
VOLUME II (REVISED 1970)

CRYOGENIC MATERIALS DATA HANDBOOK

VOLUME II

SECTIONS D, E. F, G, H AND I

F. R. SCHWARTZ, et al
MARTIN MARIETTA CORPORATION

COMPILER
M. KNIGHT
AIR FORCE MATERIALS LABORATORY

FOREWORD

This report is a compilation of several reports that were prepared by the Martin Marietta Corporation, Denver Division, Denver, Colorado, under several Air Force Contracts between 1964 and 1968. These contracts were initiated under Project 7381 "Materials Application", Task 738106 Engineering and Design Data". The contracts were administered under the Air Force Materials Laboratory, with Mr. Marvin Knight acting as Project Engineer. Mr. Knight also performed the compilation that resulted in this report.

Fred R. Schwartzberg was the Martin Marietta Program Manager, and Richard G. Herzog was Project Engineer. Other Martin Marietta personnel that assisted during the last contract were Samuel H. Osgood, responsible for data acquisition and presentation, and Mrs. Carol Bryant assisted with data acquisition.

This manuscript was released by Mr. Knight, July 1968 for publication as an RTD Technical Report.

This technical report has been reviewed and is approved.

A. Olevitch

A. OLEVITCH
Chief, Materials Engineering Branch
Materials Support Division
Air Force Materials Laboratory

ABSTRACT

The "Cryogenic Materials Data Handbook" contains mechanical and physical property data and information on 88 metallic and non-metallic materials, organized in eleven section. The Handbook also contains Material, Property and Cumulative indices and a complete list of references.

(6-68)

MATERIAL INDEX

PROPERTY INDEX

a. Yield Strength (0.2% offset)
b. Tensile Strength
c. Elongation
d. Reduction of Area
e. Notch Tensile Strength
f. Fracture Toughness
g. Weld Tensile Strength
h. Stress-Strain Diagram
i. Modulus of Elasticity
j. Impact Strength
k. Hardness
l. Modulus of Rigidity
m. Compressive Strength
n. Compressive Modulus
o. Fatigue Strength
p. Shear Strength
q. Shear Modulus
r. Flexural Strength
s. Flexural Modulus
t. Thermal Expansion
u. Poisson's Ratio
v. Thermal Conductivity
w. Resistivity
x. Specific Heat

CUMULATIVE INDEX

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x
Volume I																								
A.1	1	1	1	2				1	1	1	1				1					1		5	4	
A.2	5	5	5	5	5	4	1	2	1	1					4	1				1		5		
A.3	1	1	1	1				1	1	1					1					1				
A.4	5	5	5	5	5			1	1	1	1				1					1		5	4	
A.5	5	5	5	5	5	4	5	2	1	1					4	2				1		5		
A.6	5	5	5	5	5		3																	
A.7	5	5	5	5			3															5		
A.8	3	3	3		3		3		1													4	4	
A.9	5	5	5	5	5		4			5					4							5		
A.10	4	4	4		4		4															5		
A.11	3	3	3	3	3		3															5		
A.12	5	5	5	5	5		5	2	1	1					4					1				
A.13	5	5	5	5	5		1	2	1	1	1				1	2				1				
A.14	3	3	3	3	3		3																	
A.15	5	5	5				5	2	4	2					4	1				1		5		
A.16	5	5	5	5	3	4		1	5	5	1				4					1		5		
A.17	4	4	4	4	4	4	4																	
A.18	4	4	4		4		4		4						4									
A.19	3	3	3		3		4																	
A.20	4	4	4																					
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B.10										1										1				
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C.9	5	5	5	5						5														
Volume II																								
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H.7		2								2			2	2				2	2					
H.8		2							2				2	2						5		5		

The letters and numbers in the left column denote the general group and specific material as listed in the index. The letters of the top row denote a property, and the numbers within the squares refer to the last progress report in which data represented by the coordinates was issued as follows 1 = ML-TDR-64-280 (Basic Handbook), 2 = Supplement No. 1; 3 = Supplement No. 2; 4 = Supplement No. 3; and 5 = Supplement No. 4. (6-68)

NOT REPRODUCIBLE

ABBREVIATIONS AND TERMS

UTS	ultimate tensile strength
PSI	pounds per square inch
KSI	1000 pounds per square inch
°F	degrees Fahrenheit
HR	hour, hours
MIN	minute, minutes
IN.	inch, inches
CM	centimeter, centimeters
MM	millimeter, millimeters
DIA	diameter
FT-LB	foot-pounds
BTU	British Thermal Units
WQ	water quench
OQ	oil quench
AC	air cool
FC	furnace cool
R	stress ratio (minimum stress/maximum stress in fatigue tests)
K_T	theoretical stress concentration factor, according to Peterson's data
LONG., L	longitudinal grain direction
TRANS, T	transverse grain direction
DPH	Diamond Pyramidal Hardness
NOL	Naval Ordnance Laboratory
T, H, O	Temper designations for aluminum alloys (i.e. T6, H38); refer to materials guide for detailed discussion of aluminum temper designations
TIG	Tungsten-inert-gas

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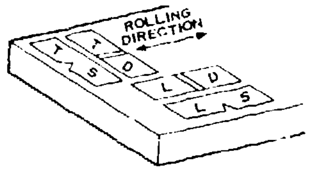
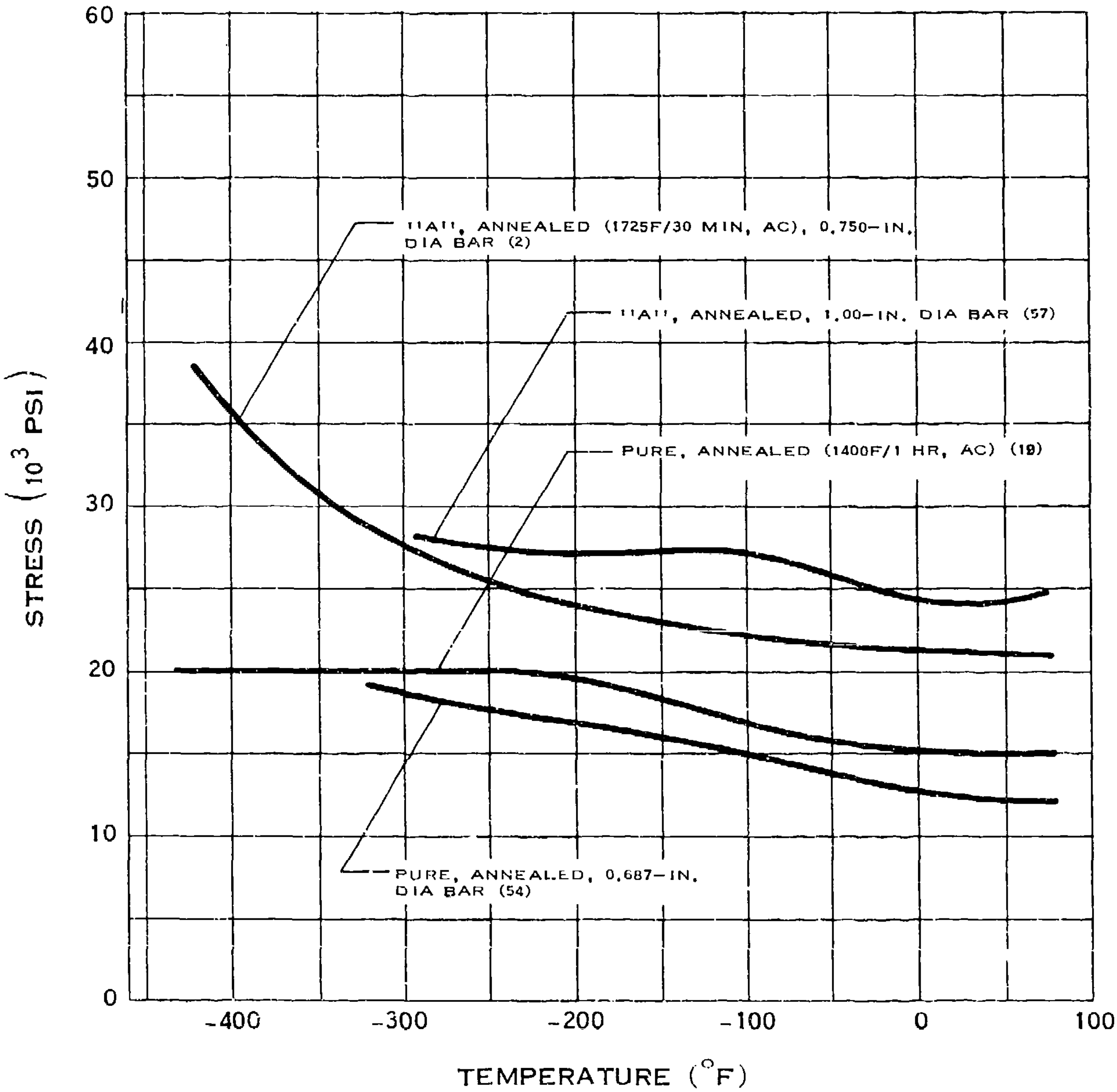
MIG	metallic-inert-gas
----	insufficient data to accurately show shape of curve; for fracture toughness data, indicates yielding
K_c	plane stress fracture toughness
K_{Ic}	plane strain fracture toughness
G_c	plane stress energy release rate
G_{Ic}	plane strain energy release rate
E	modulus of elasticity
μ	Poisson's ratio
CN	center-notched
SC	surface-cracked
NRB	notched-round bar
SNB	slow notched bend
W	width
A	half-crack length or crack depth
B	thickness
LS, LD, TS, TD	orientation for slow notched bend specimens



tough	behavior in notched specimens where a finite amount of gross plastic flow occurs and the strength is near or above the yield strength
fracture strength	net stress (for plane stress fracture toughness)
$\uparrow$	lower bound valve
=	equals
$\simeq$	approximately equal

D - SUPERALLOYS

D.1.a



YIELD STRENGTH OF NICKEL

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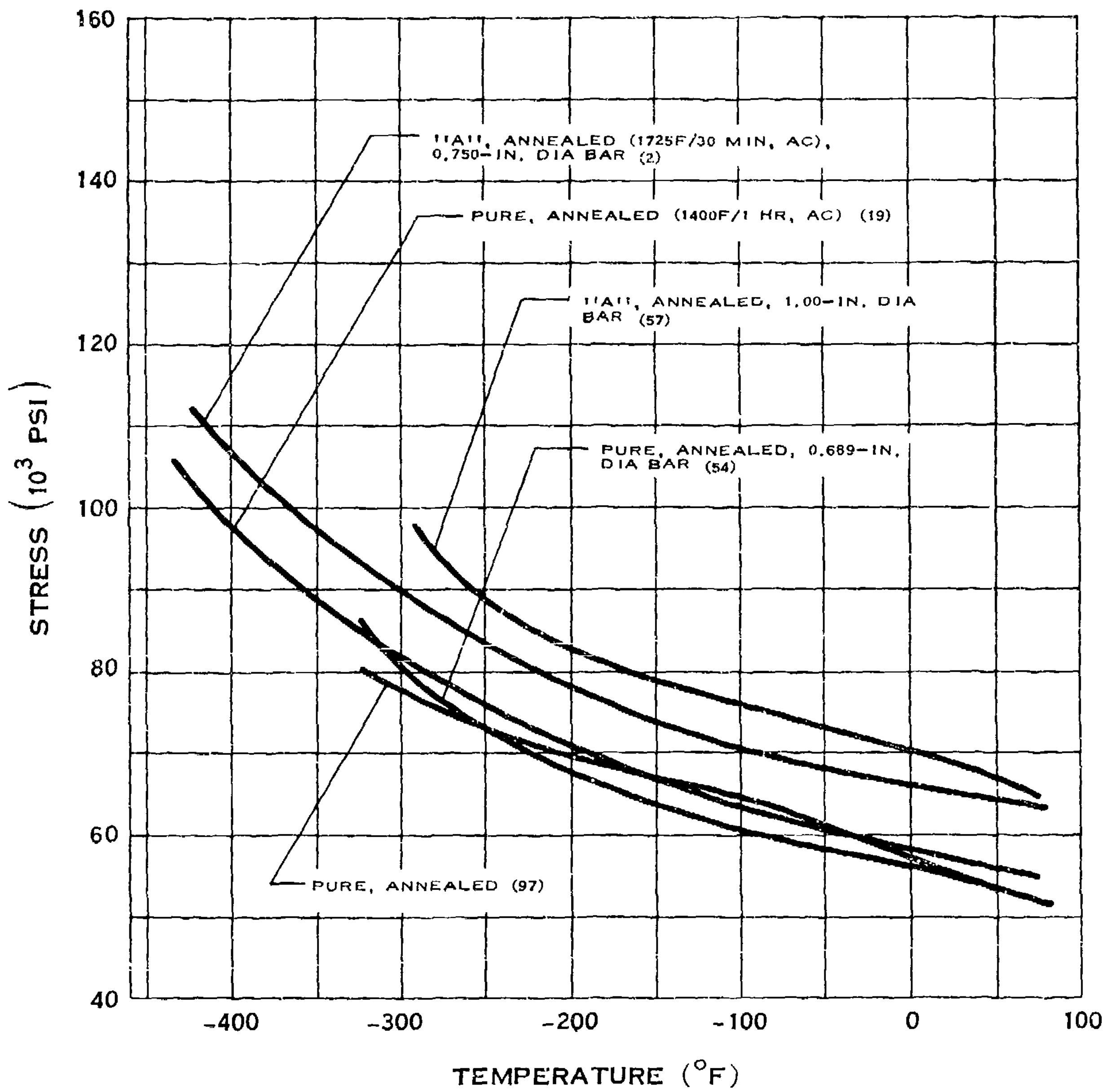
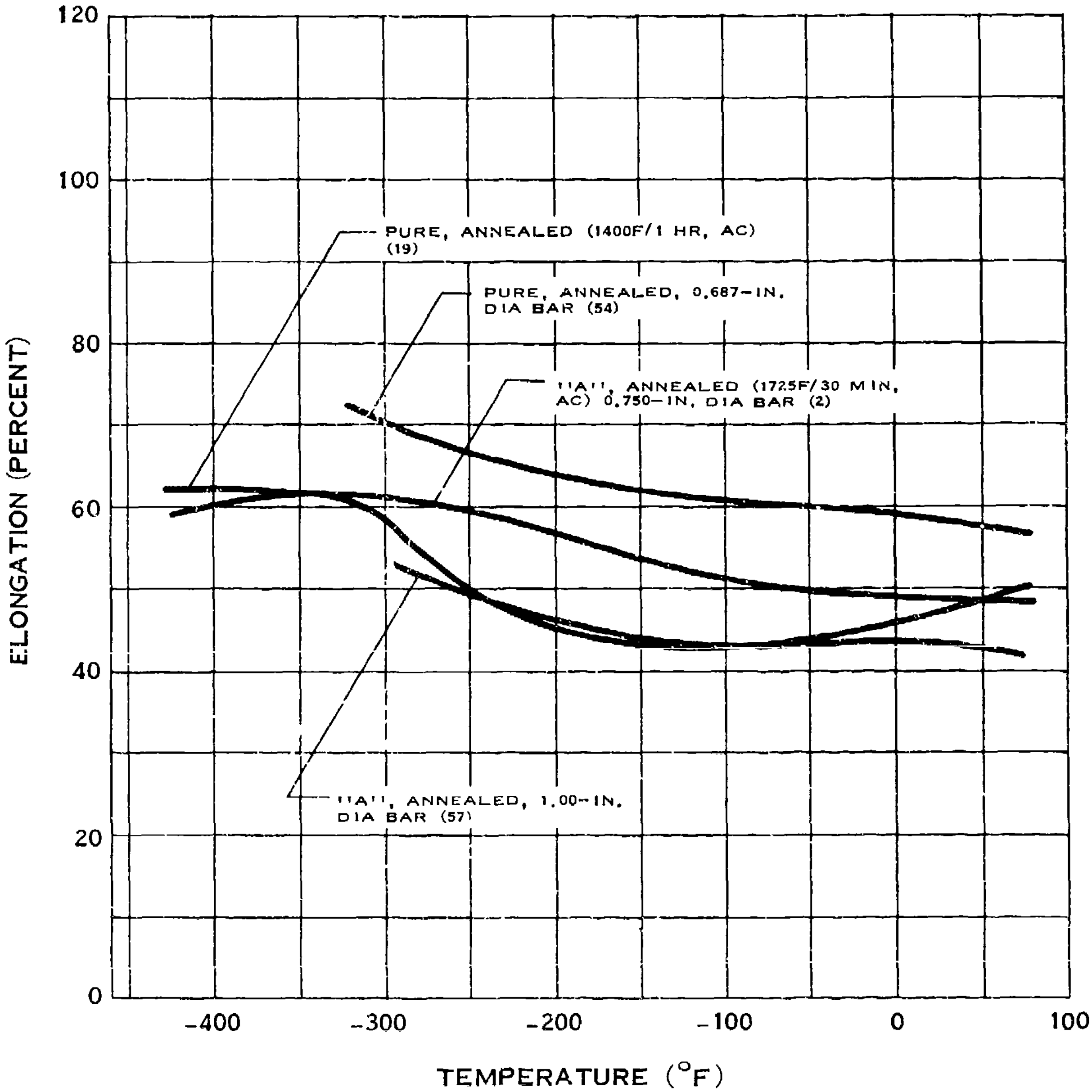
(7-64)

D.1.b



TENSILE STRENGTH OF NICKEL

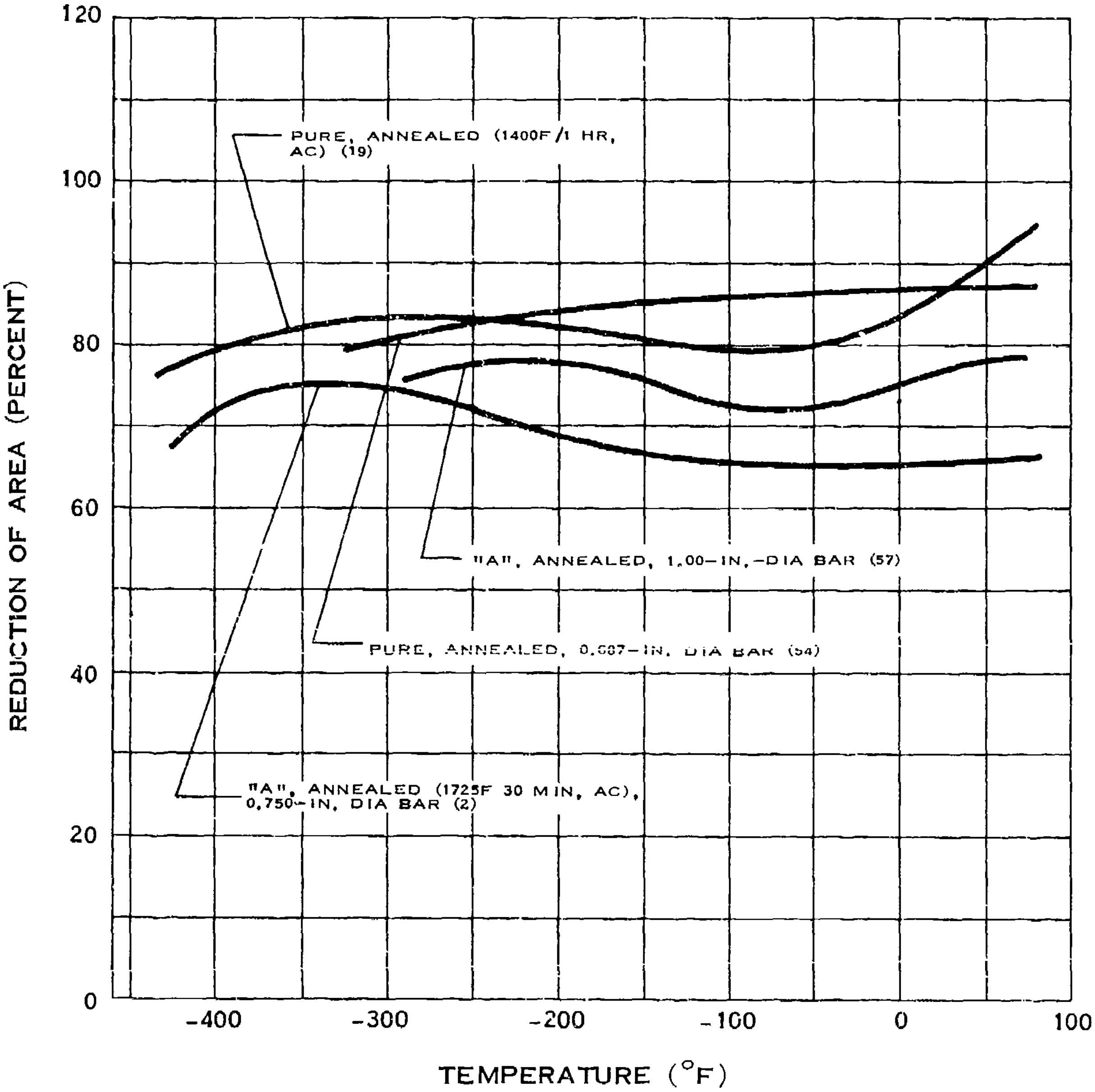
D.1.c



ELONGATION OF NICKEL

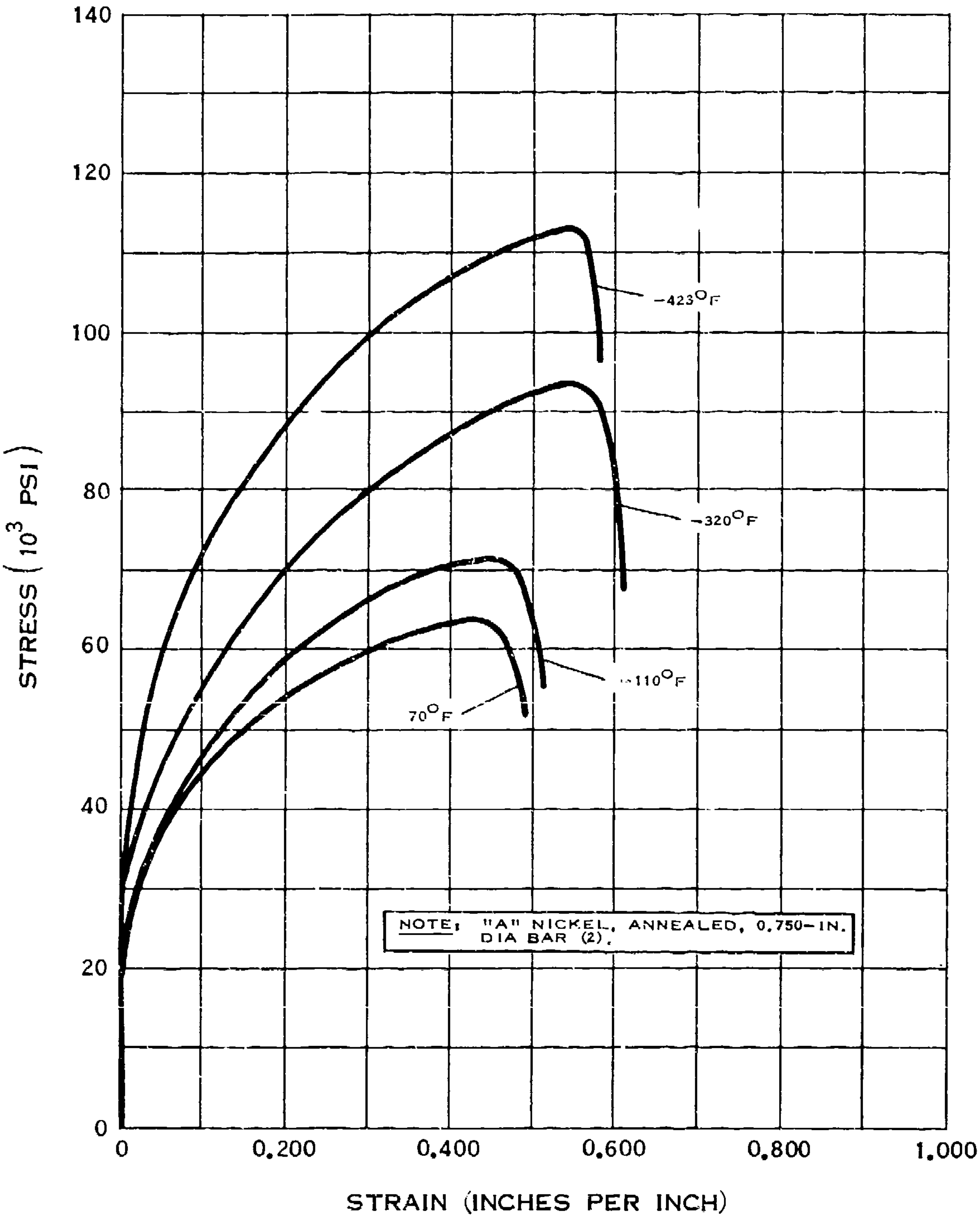
(7-64)

D.1.d

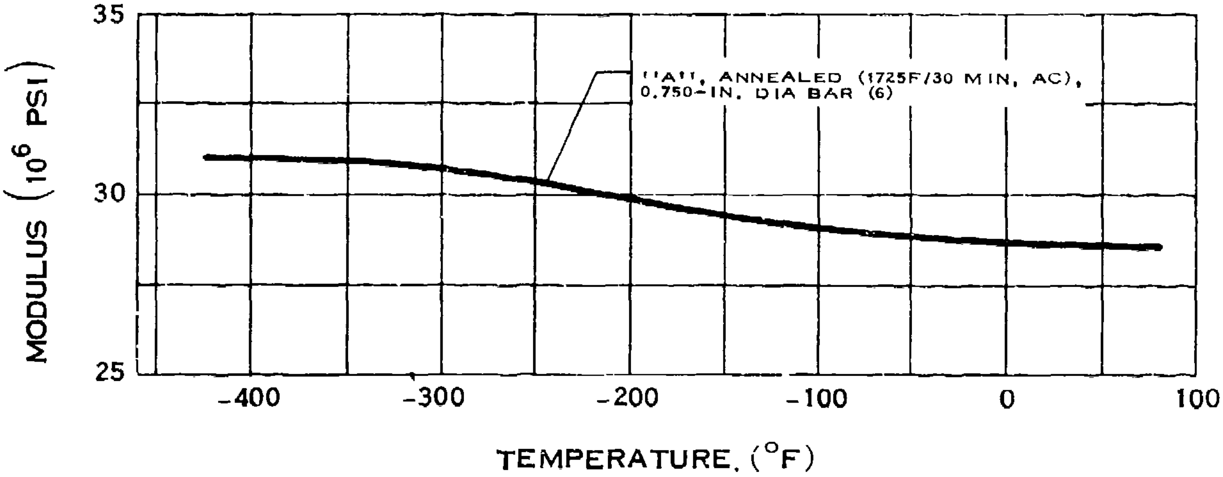


REDUCTION OF AREA OF NICKEL

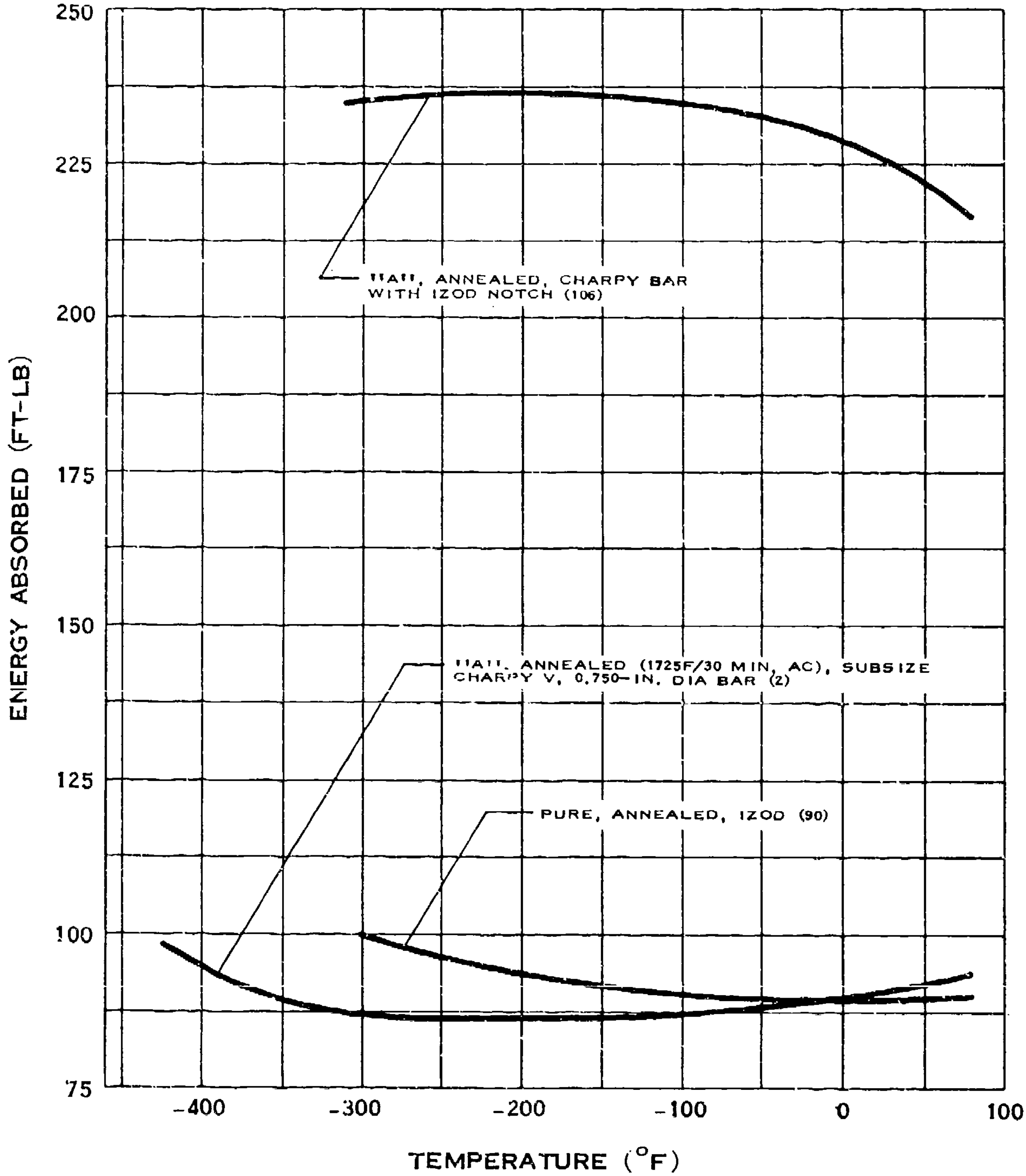
(7-64)



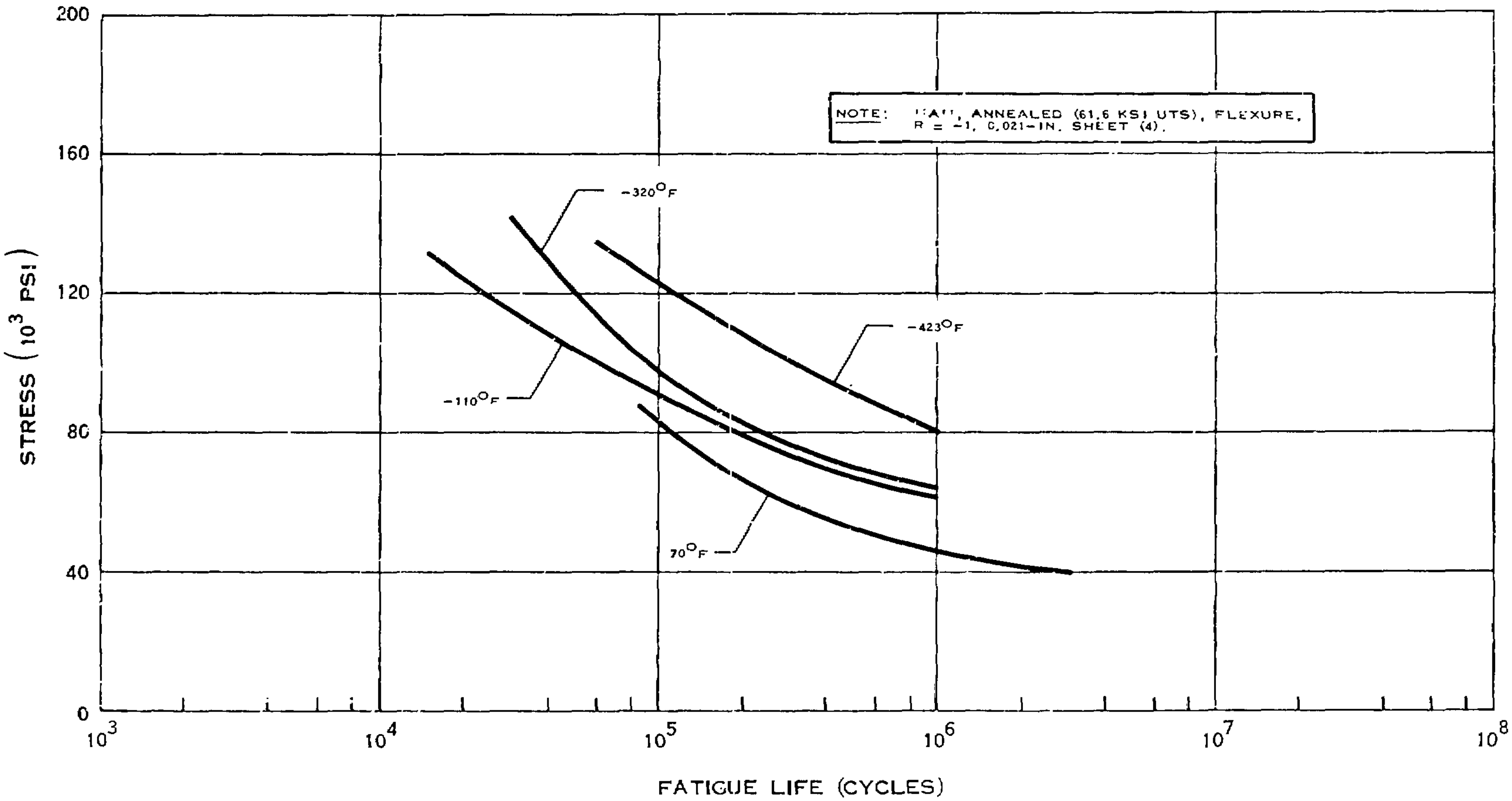
STRESS-STRAIN DIAGRAM FOR NICKEL



MODULUS OF ELASTICITY OF NICKEL



IMPACT STRENGTH OF NICKEL



FATIGUE STRENGTH OF NICKEL

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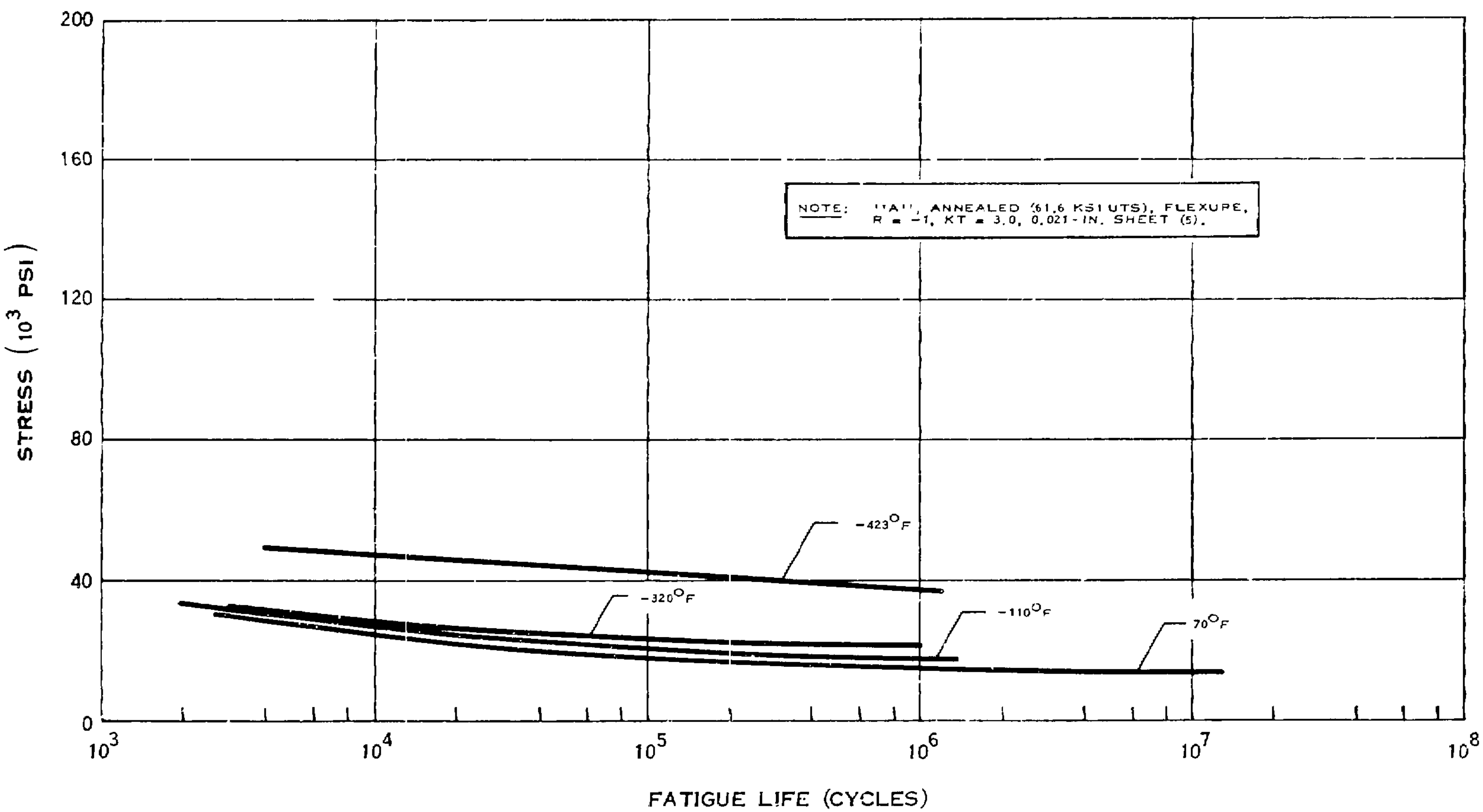

NOTCH FATIGUE STRENGTH OF NICKEL

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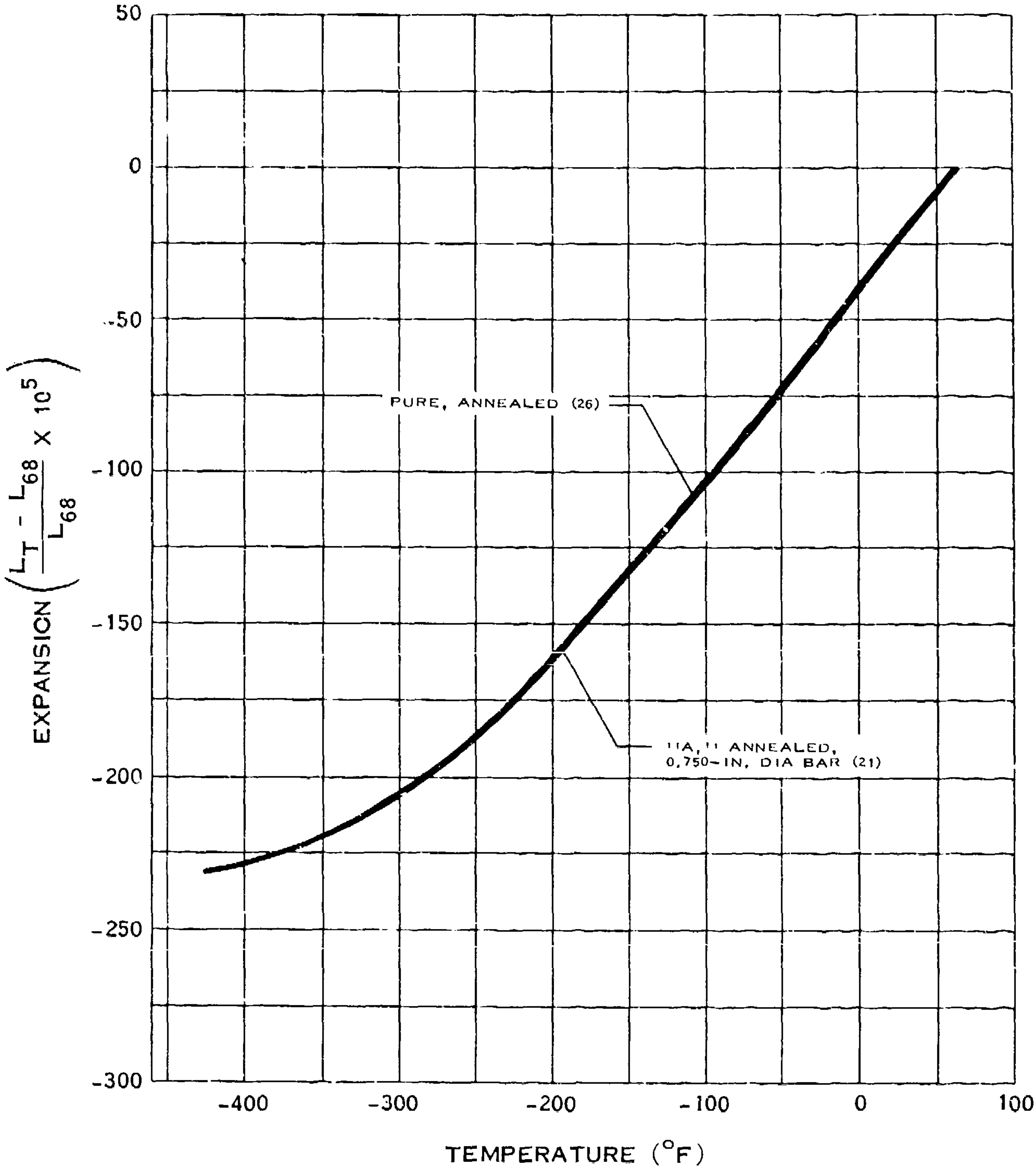
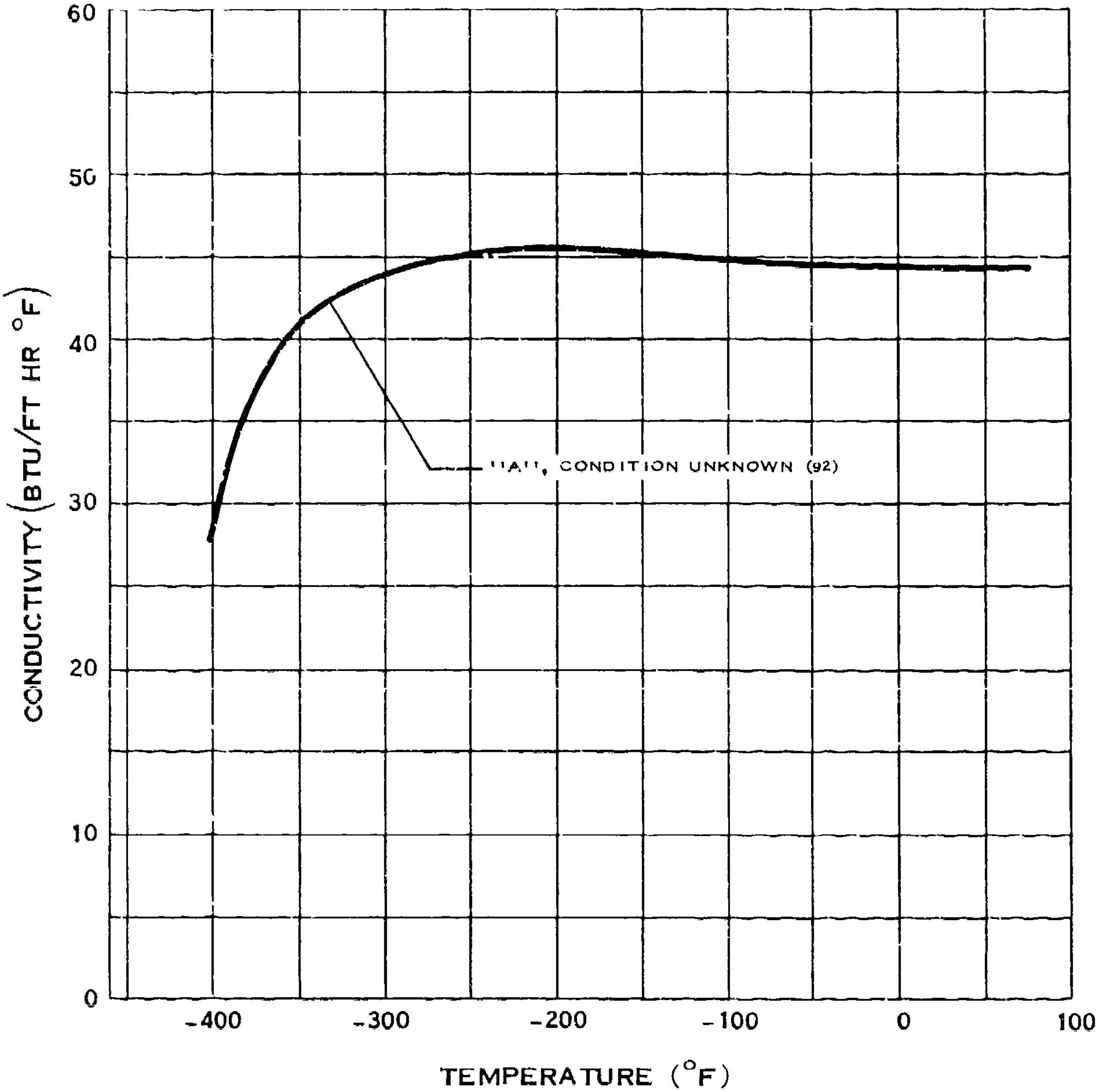


THERMAL EXPANSION OF NICKEL

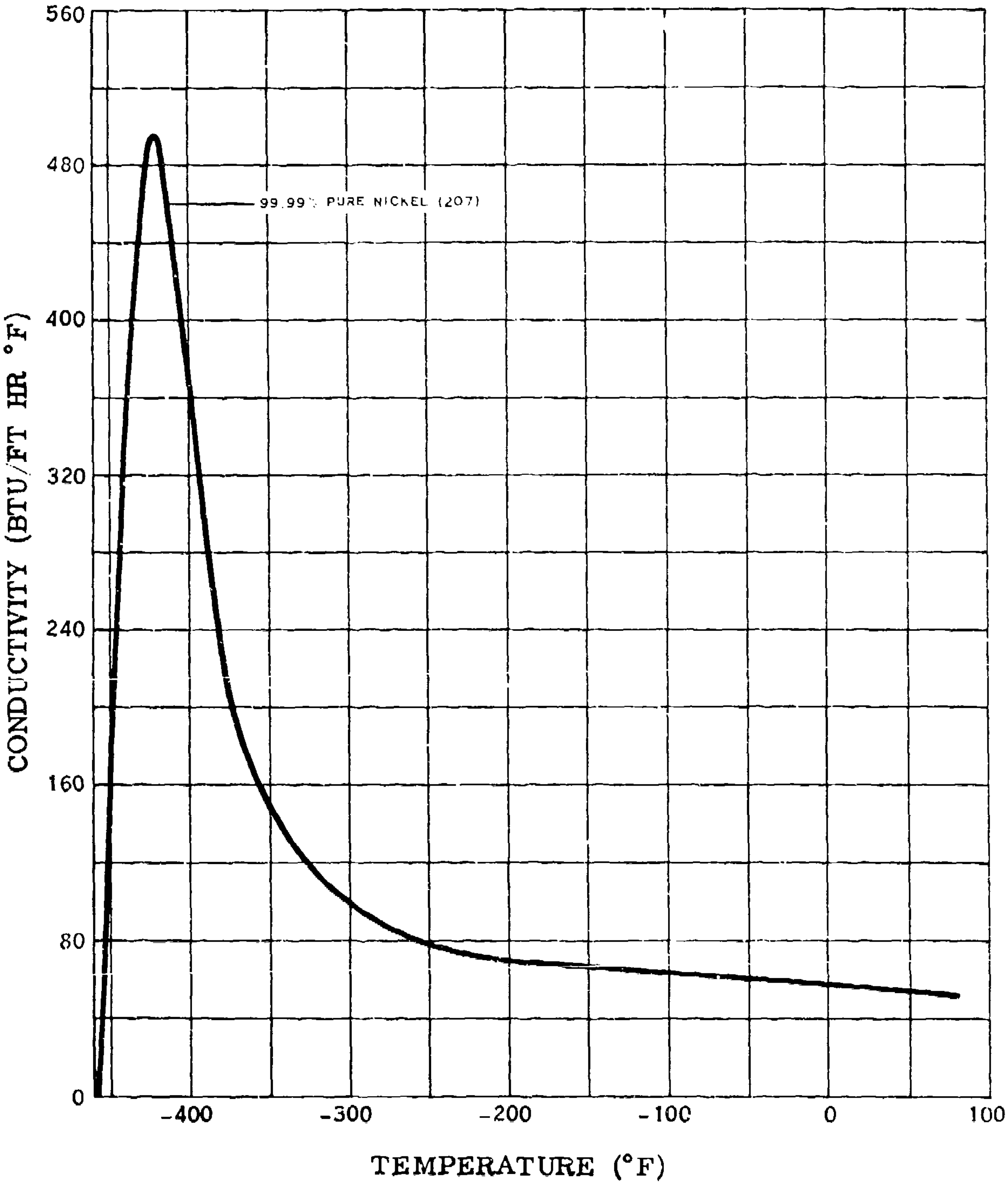
D.1.v



THERMAL CONDUCTIVITY OF NICKEL

(7-64)

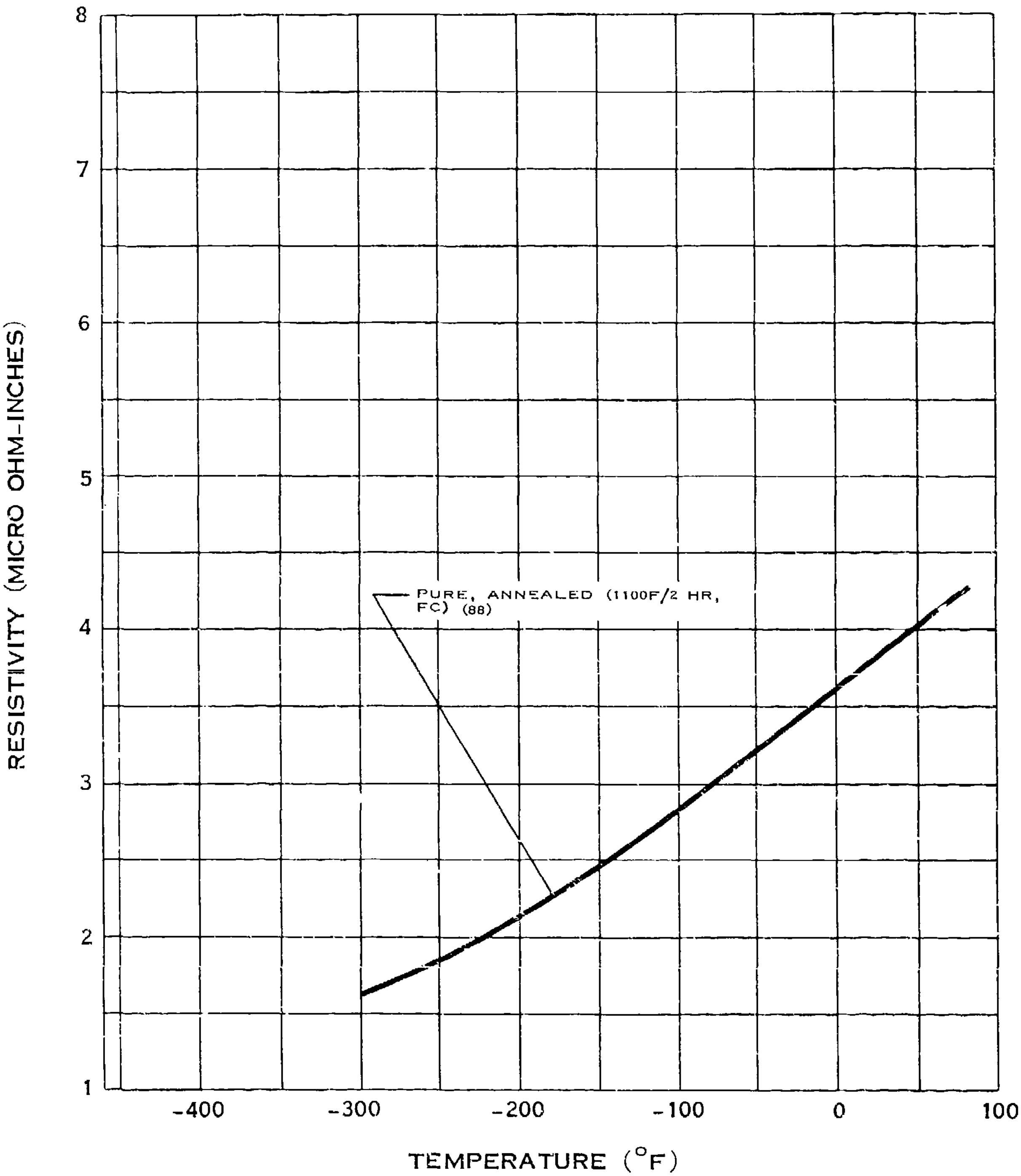
D.1.v-1



THERMAL CONDUCTIVITY OF NICKEL

(6-68)

D.1.w



ELECTRICAL RESISTIVITY OF NICKEL

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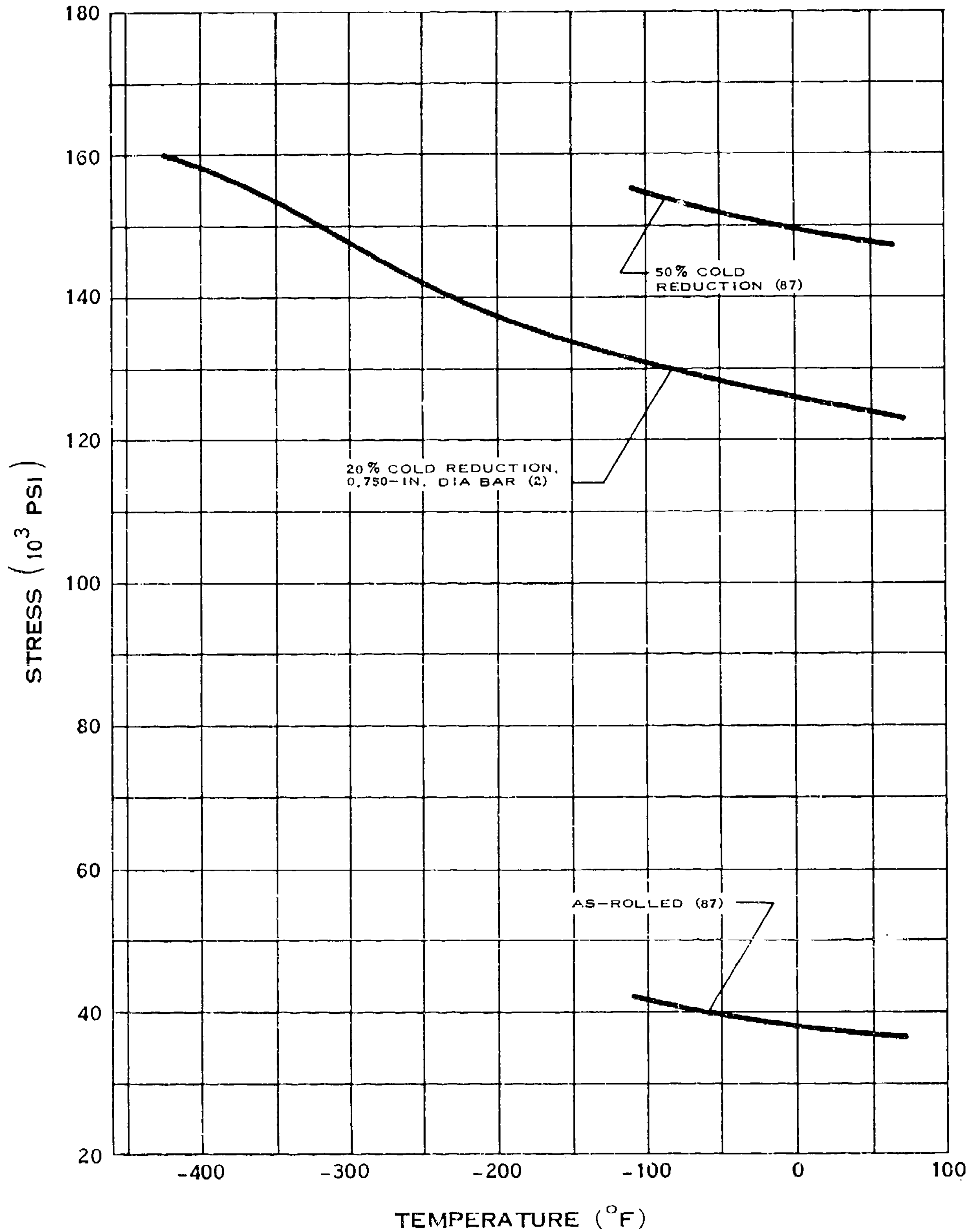

YIELD STRENGTH OF INCONEL

(7-64)

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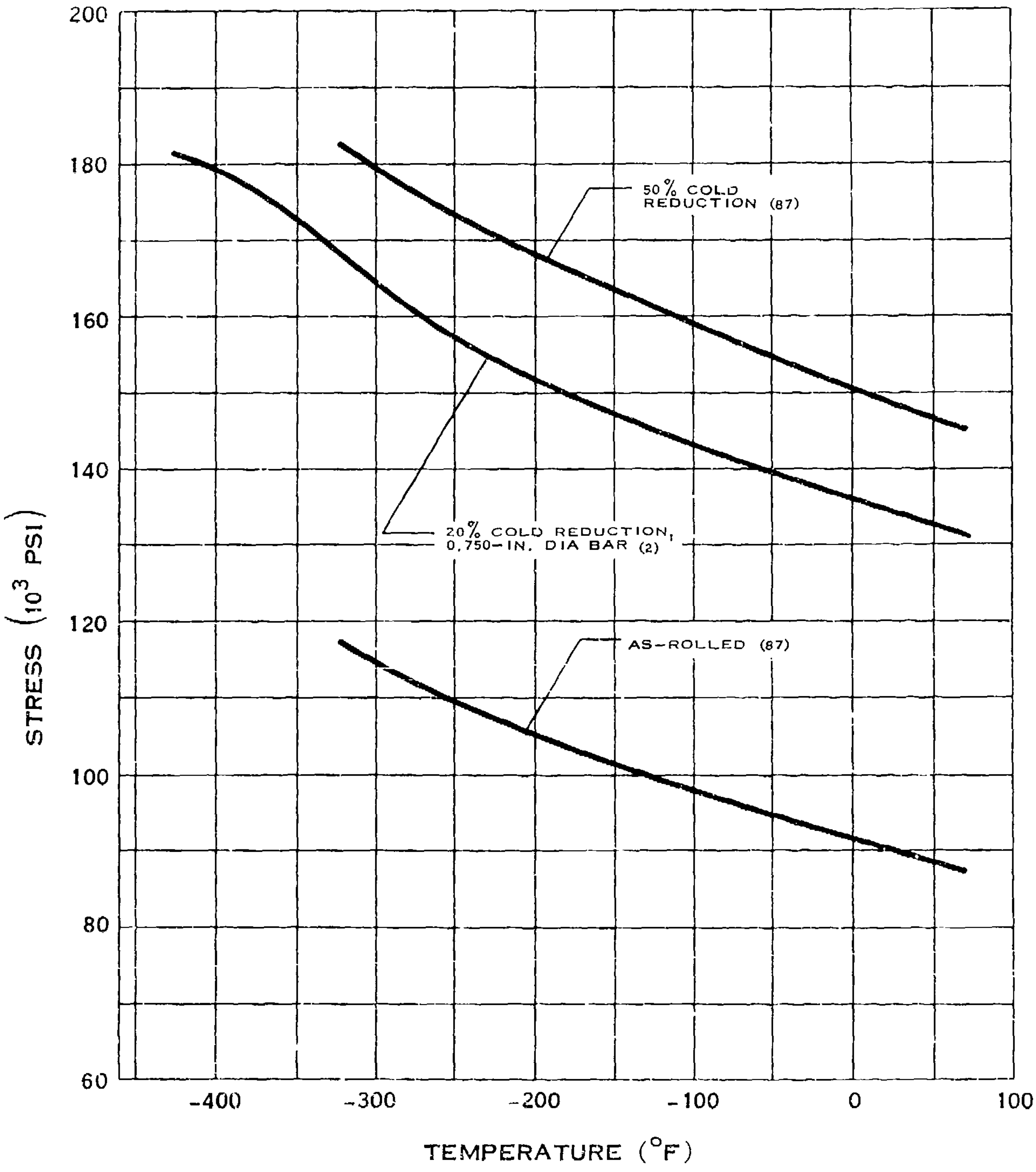
D.2.b



TENSILE STRENGTH OF INCONEL

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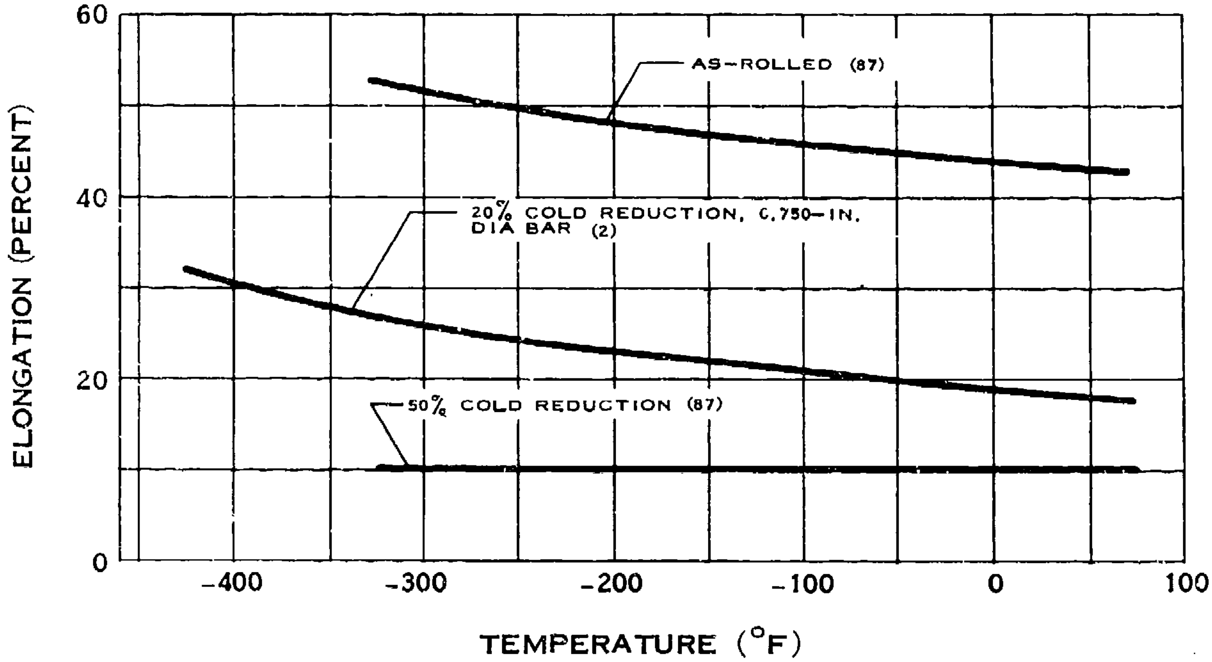
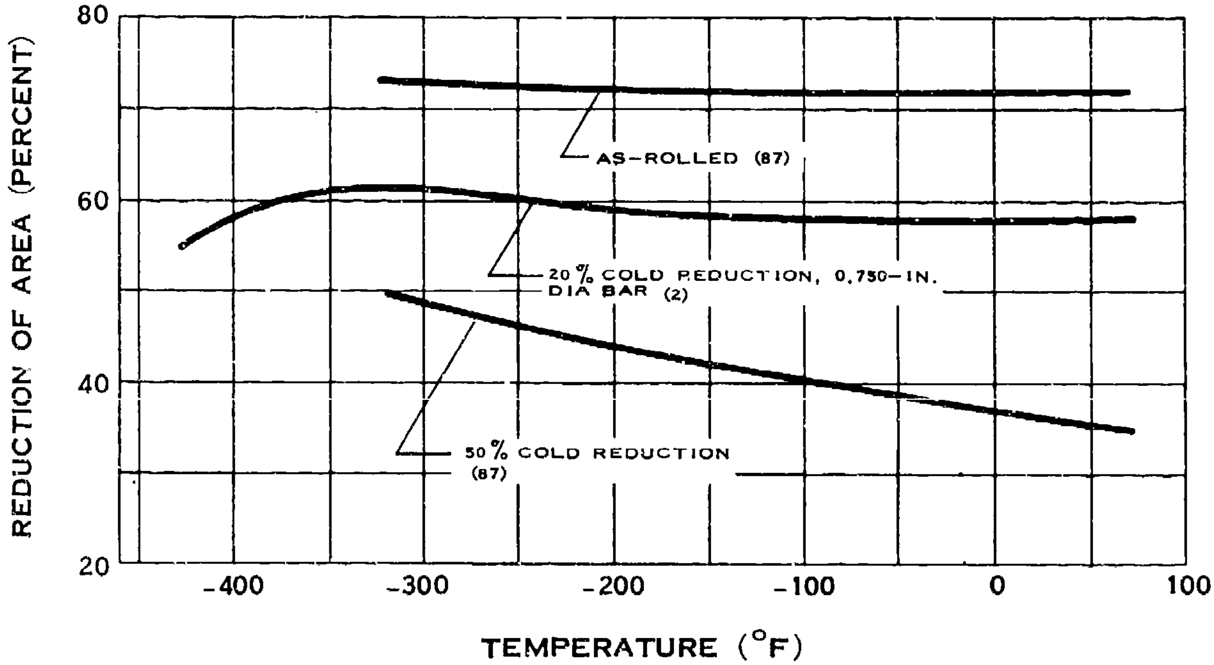
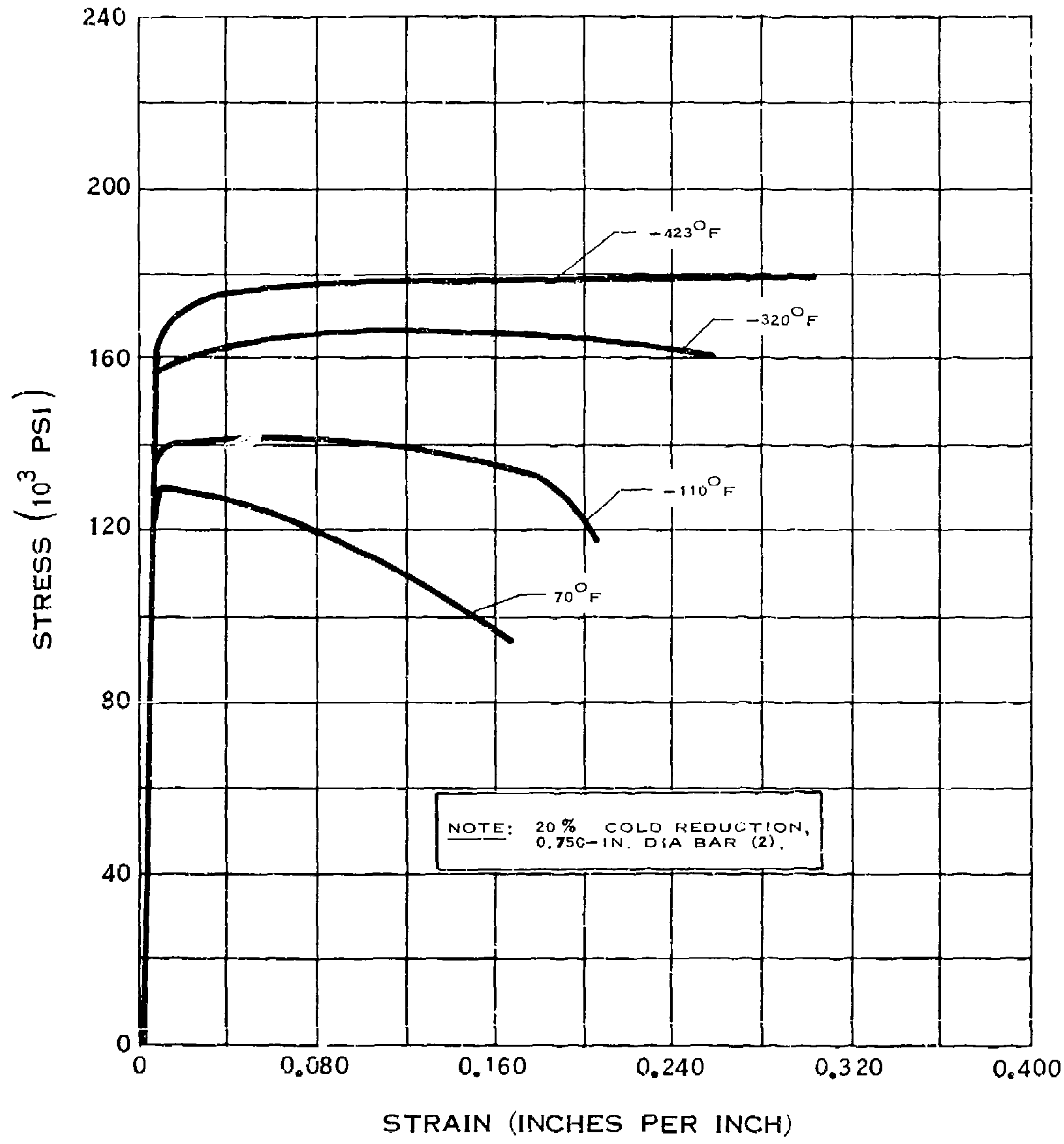


ELONGATION OF INCONEL

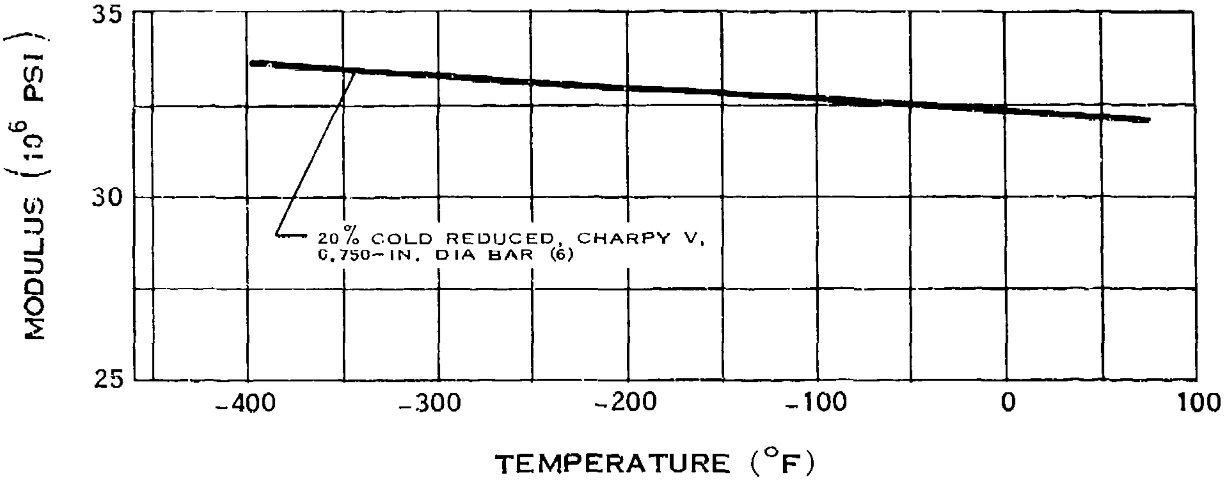


REDUCTION OF AREA OF INCONEL

D.2.h



STRESS-STRAIN DIAGRAM FOR INCONEL



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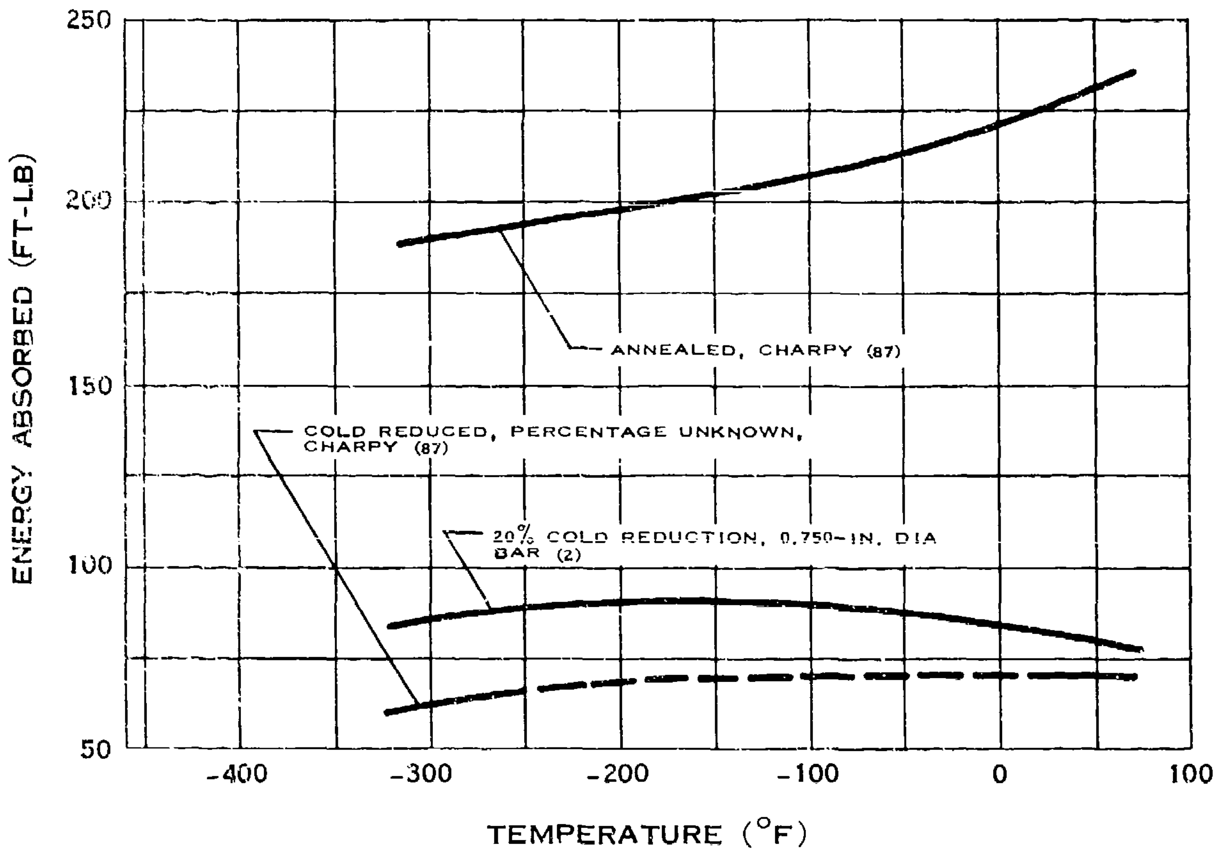

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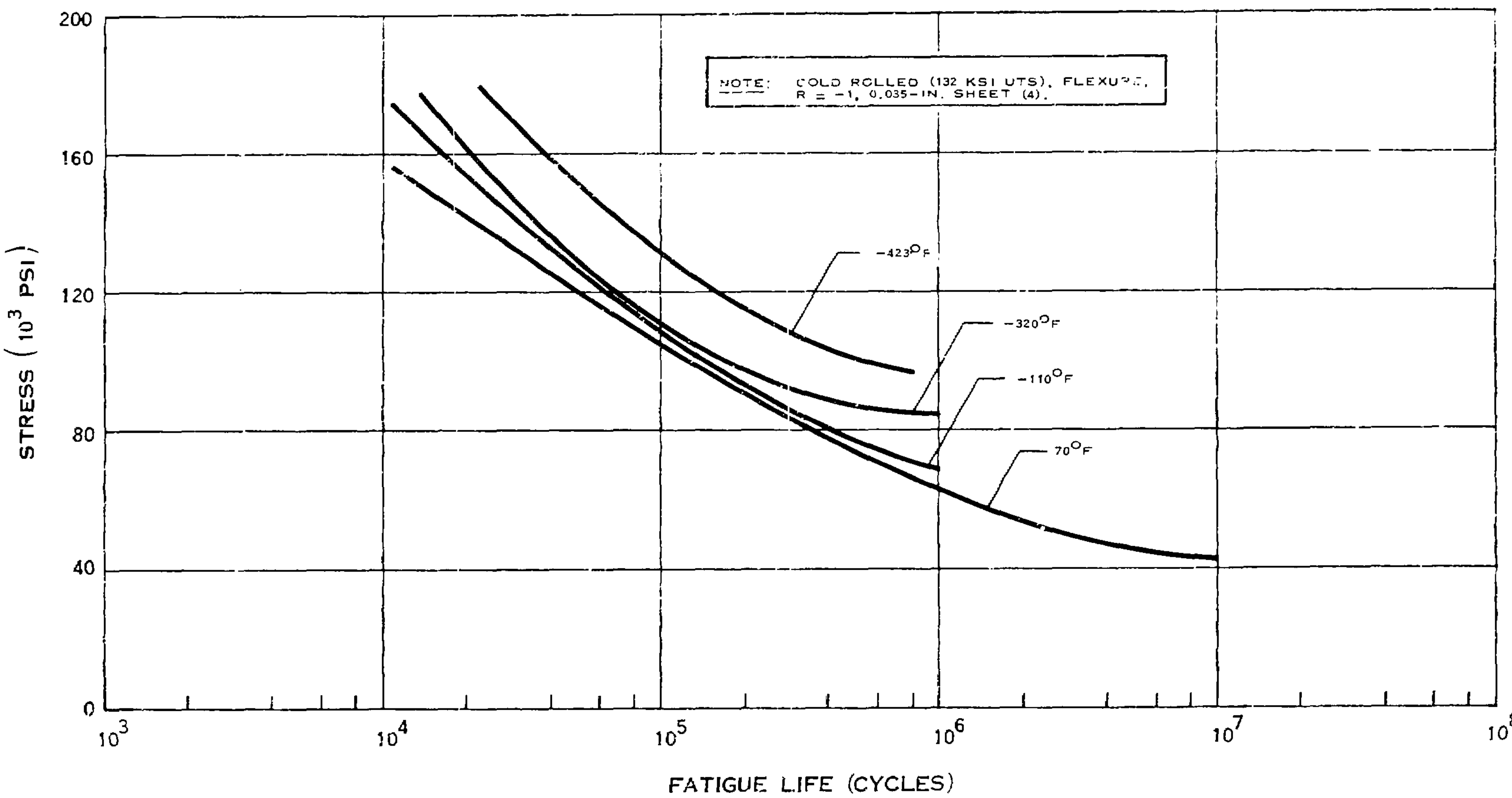

FATIGUE STRENGTH OF INCONEL

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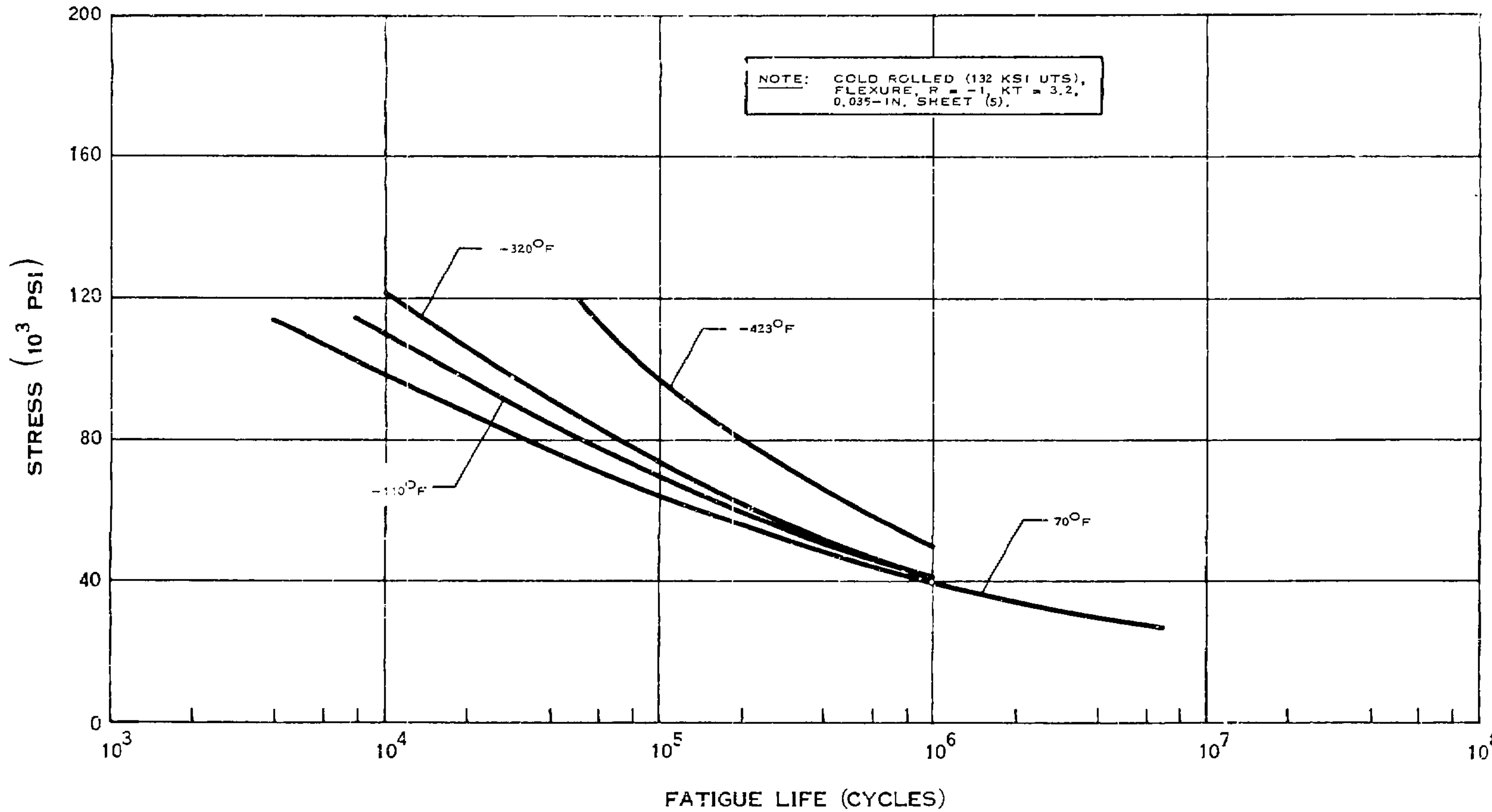

NOTCH FATIGUE STRENGTH OF INCONEL

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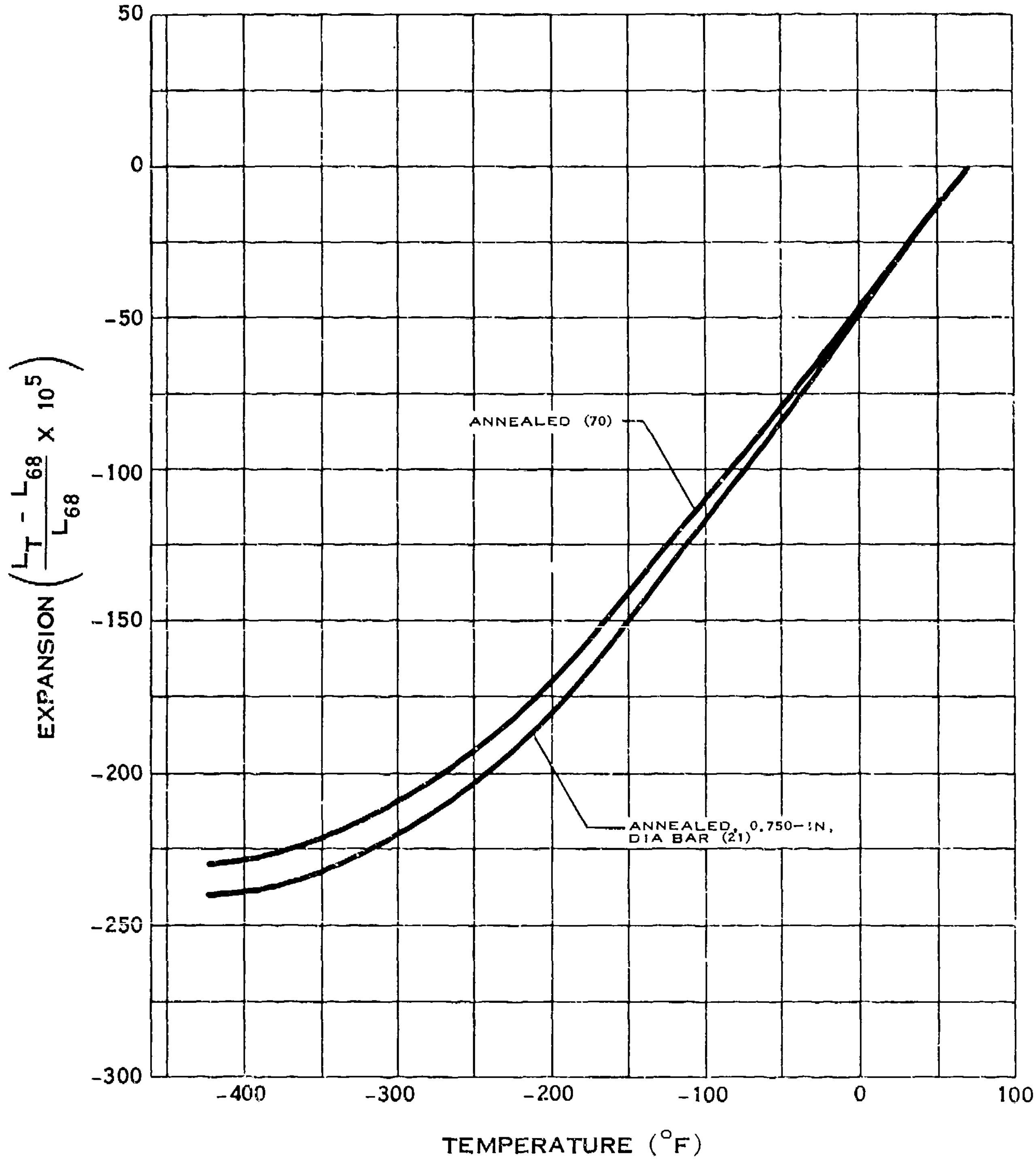
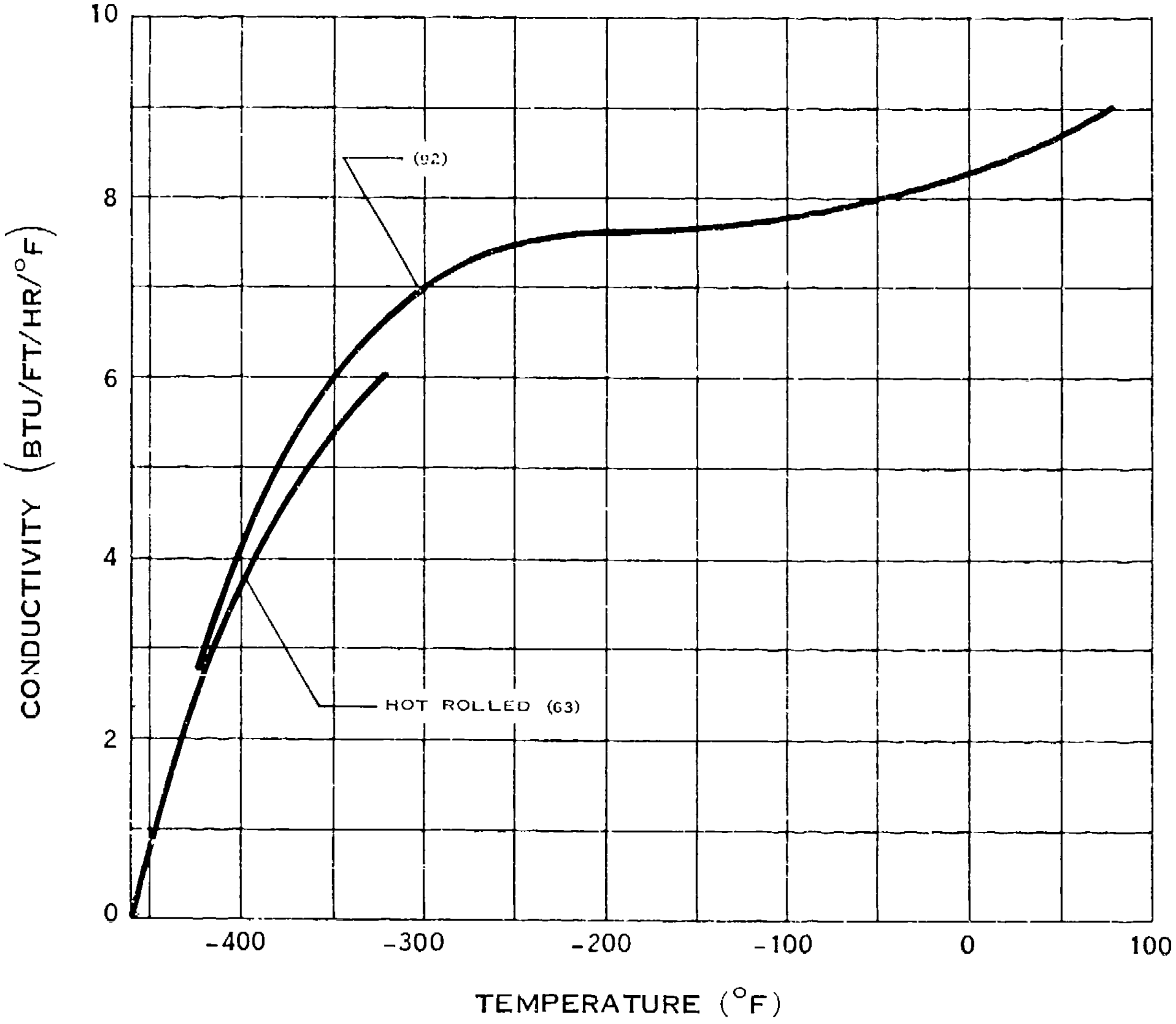


THERMAL EXPANSION OF INCONEL

D.2.v



THERMAL CONDUCTIVITY OF INCONEL

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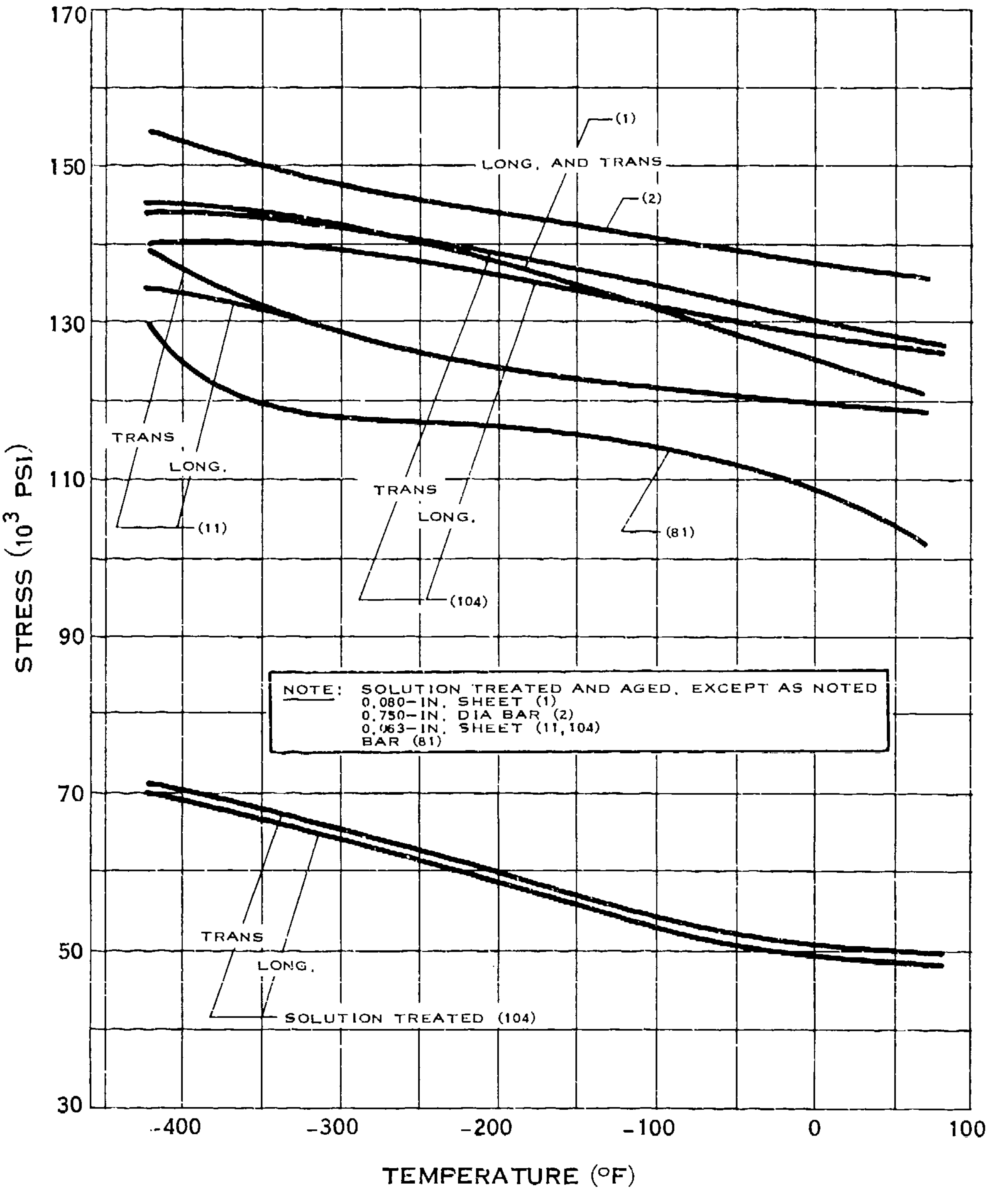

YIELD STRENGTH OF INCONEL X

(7-65)

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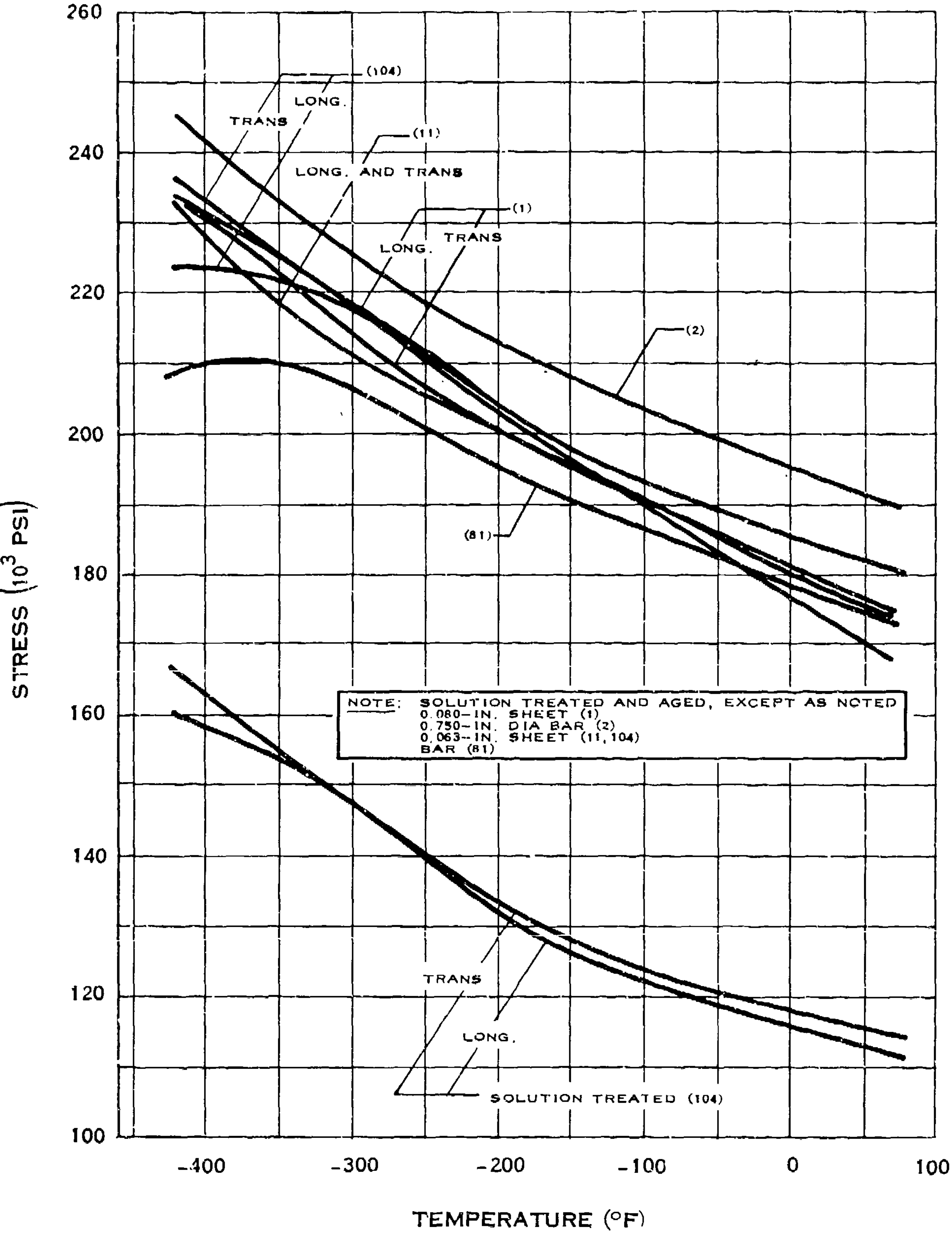
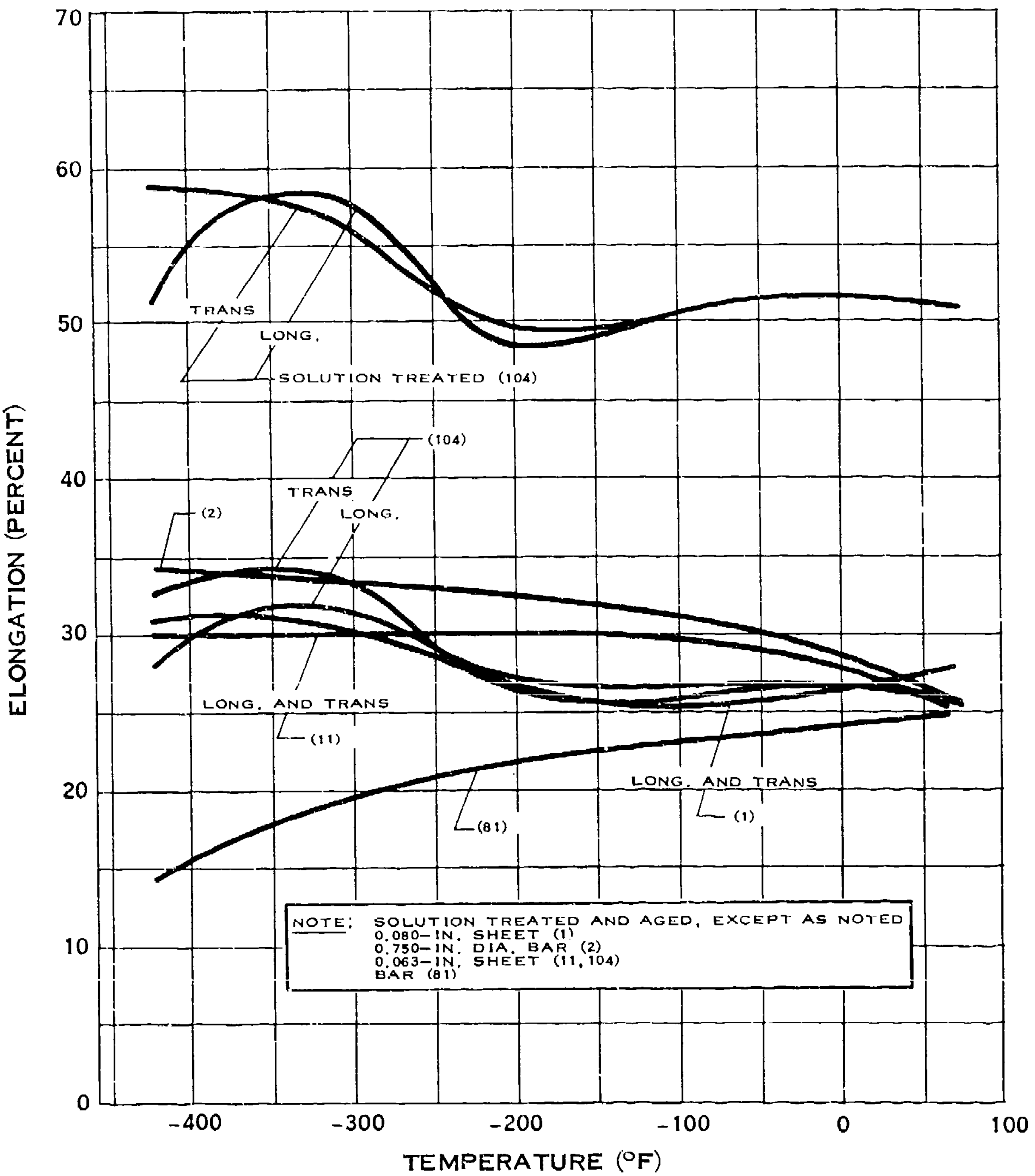


TENSILE STRENGTH OF INCONEL X

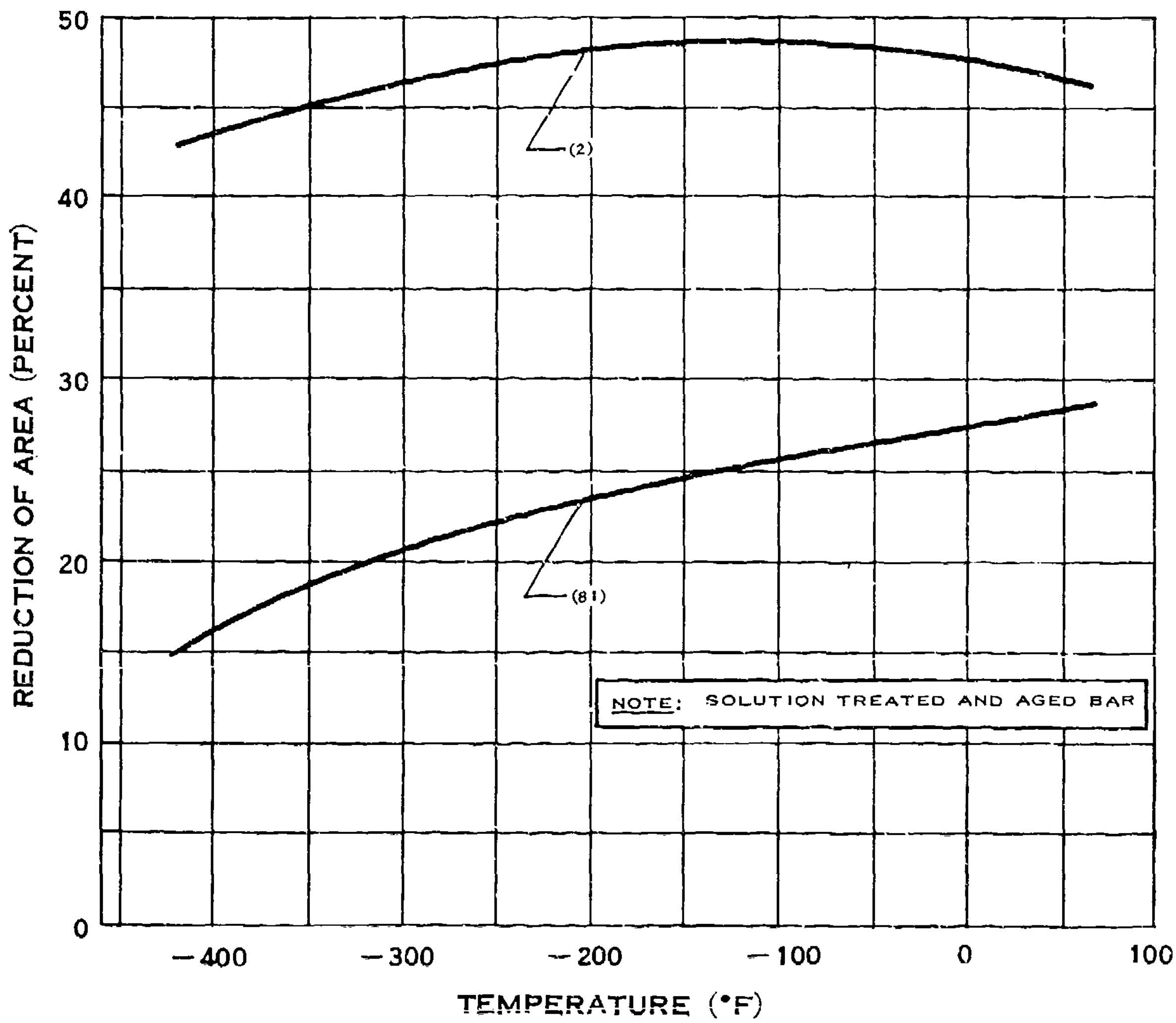
(7-65)



ELONGATION OF INCONEL X

(7-65)

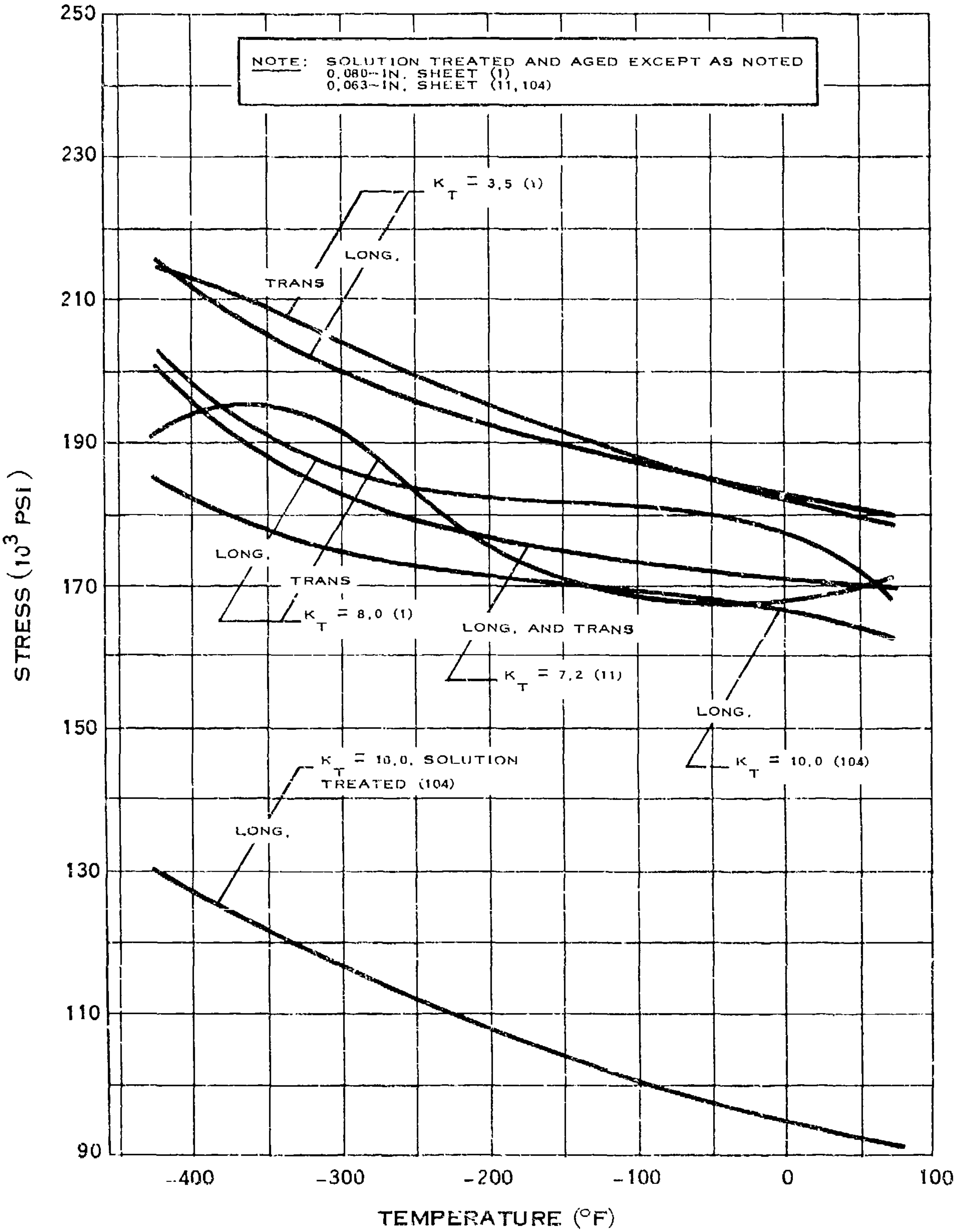
D.3.d



REDUCTION OF AREA OF INCONEL X

(7−64)

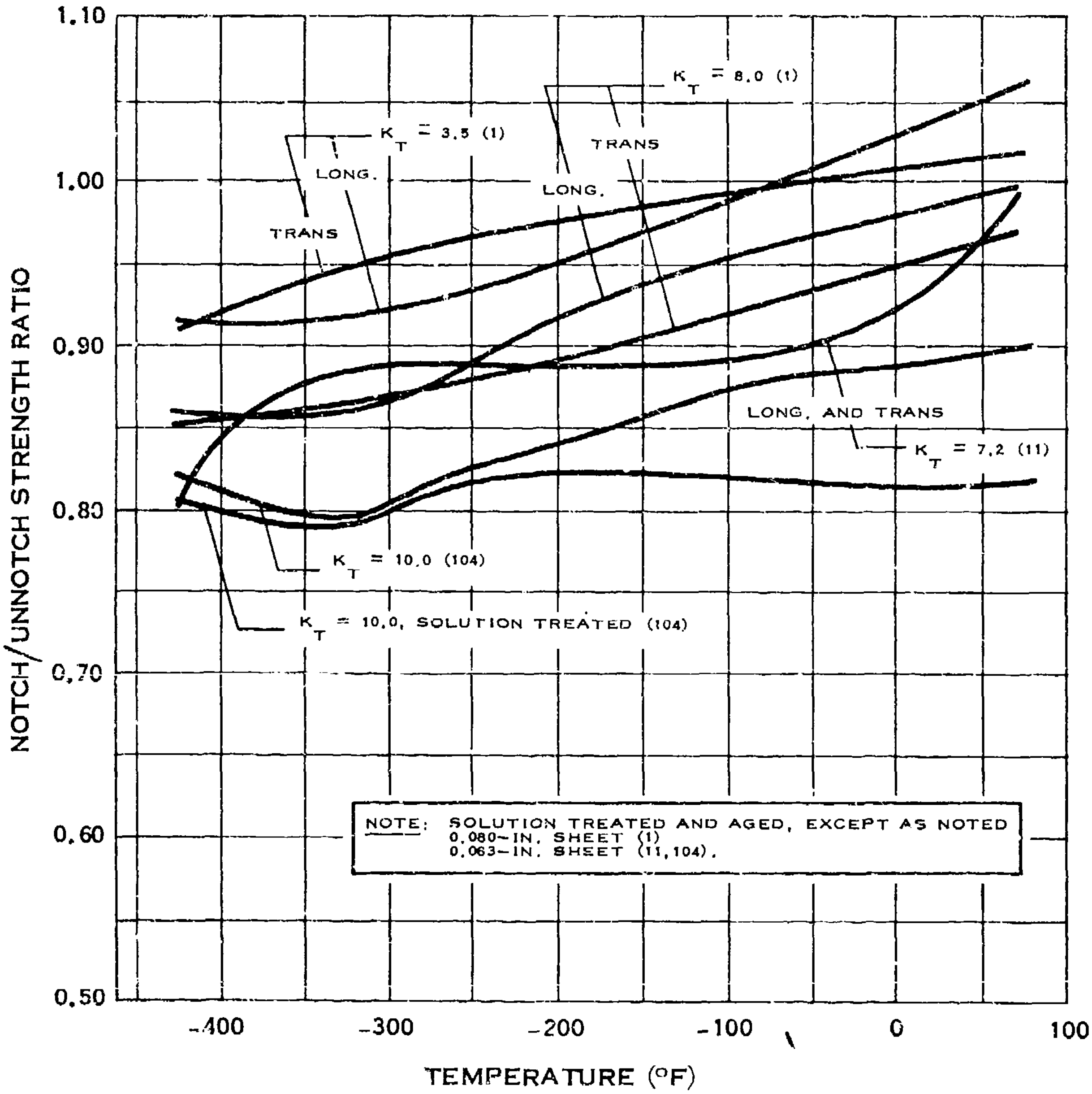
D.3.e



NOTCH TENSILE STRENGTH OF INCONEL X

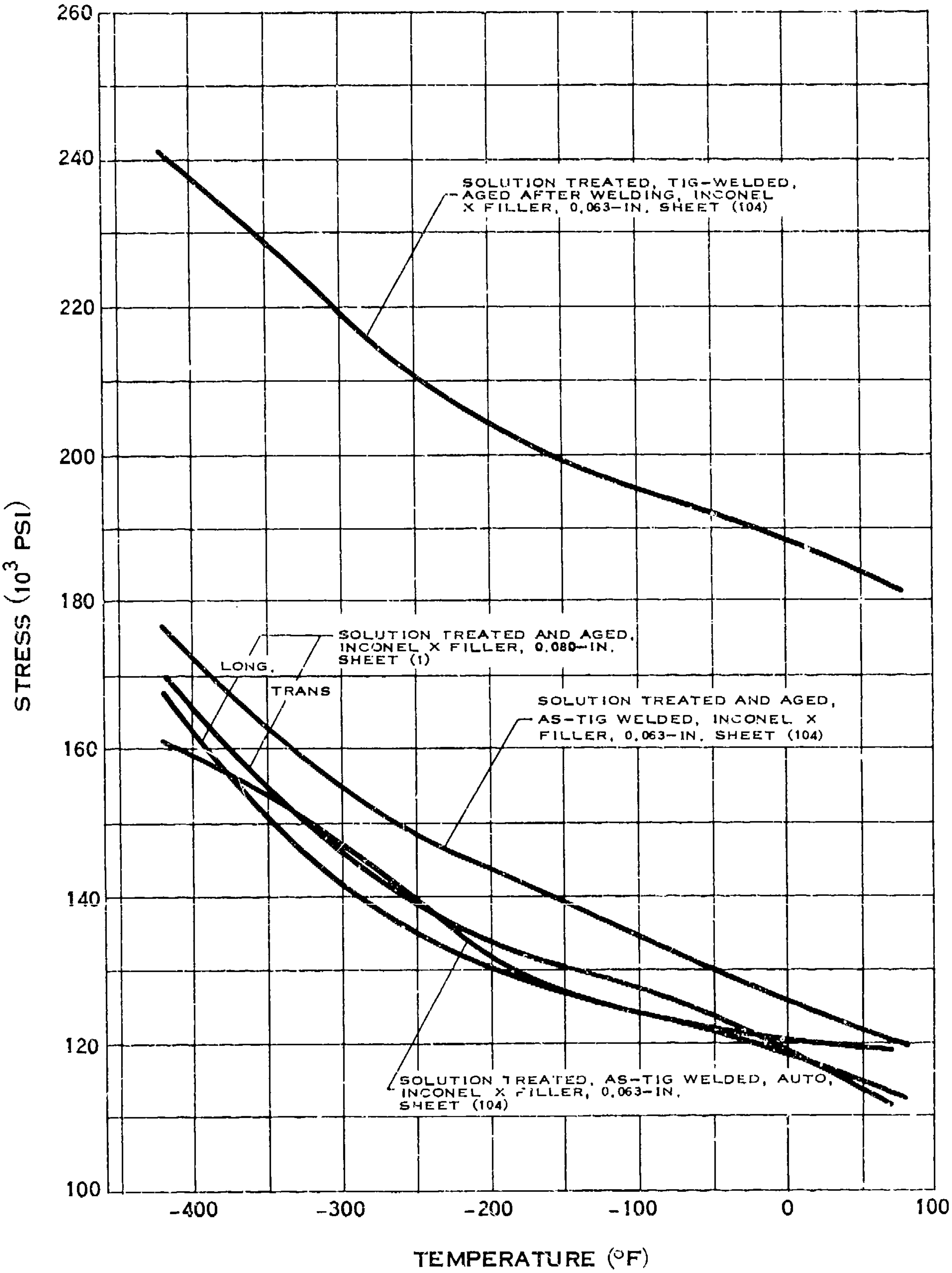
(7-65)

D.3.e-1



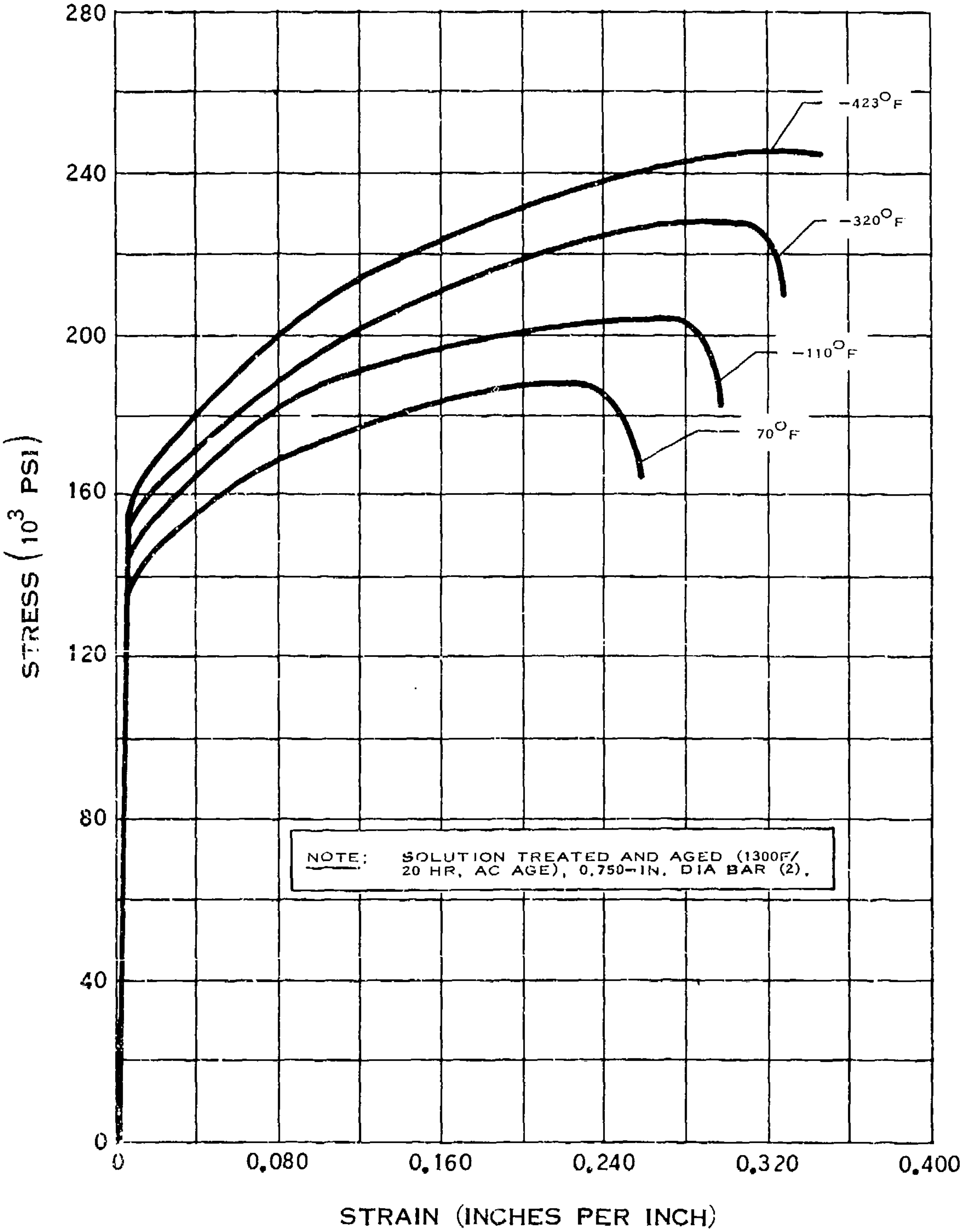
NOTCH STRENGTH RATIO OF INCONEL X

(7-65)



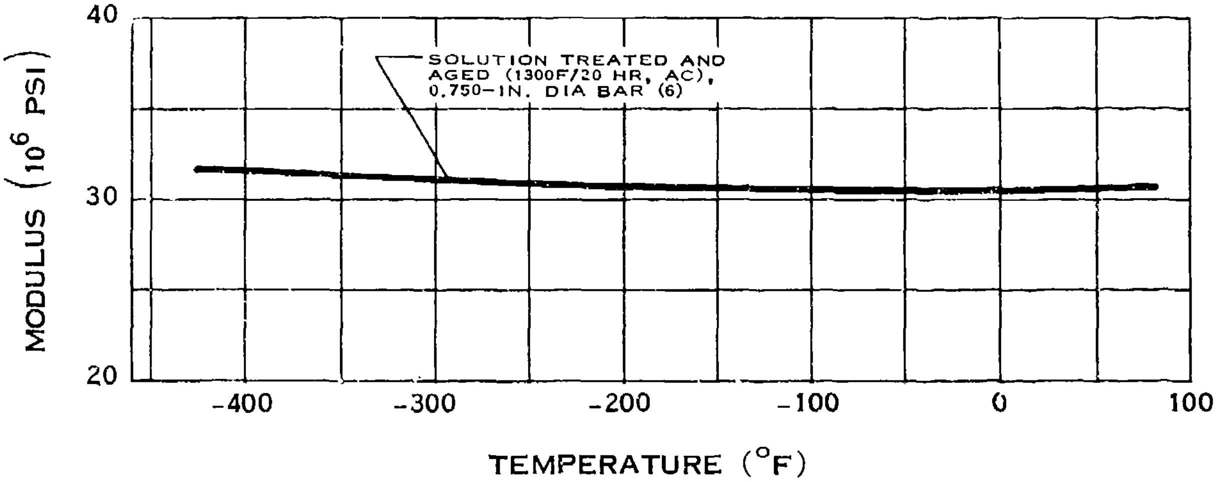
WELD TENSILE STRENGTH OF INCONEL X

(7-65)

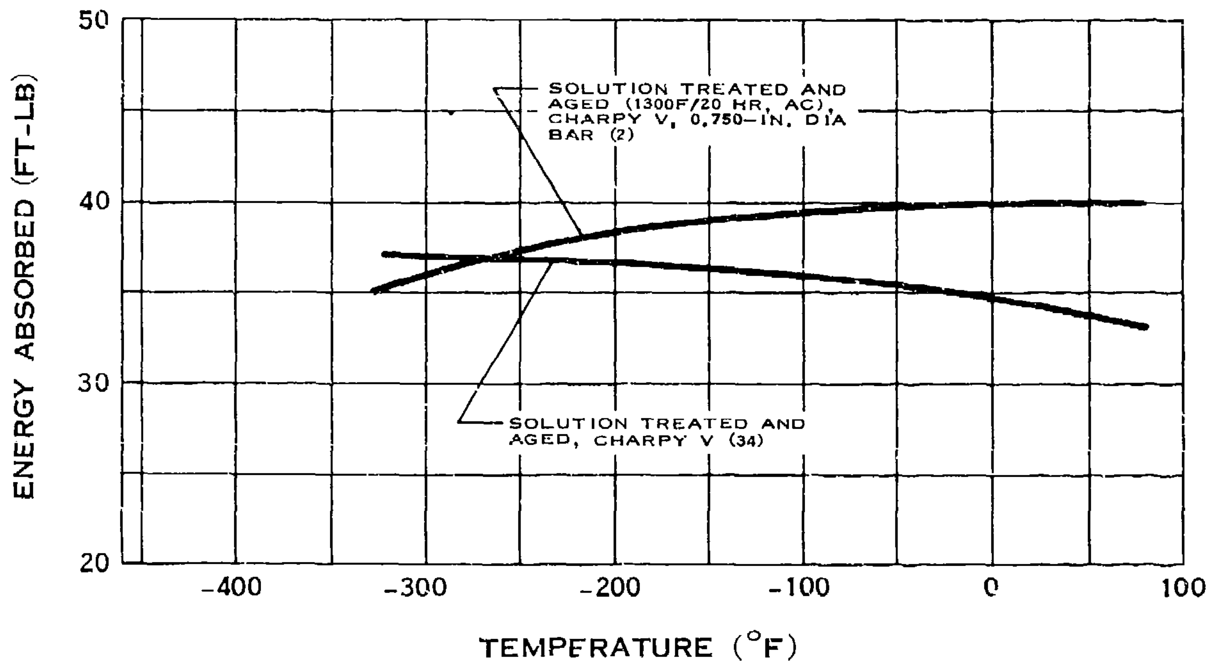


STRESS-STRAIN DIAGRAM FOR INCONEL X

(7-64)



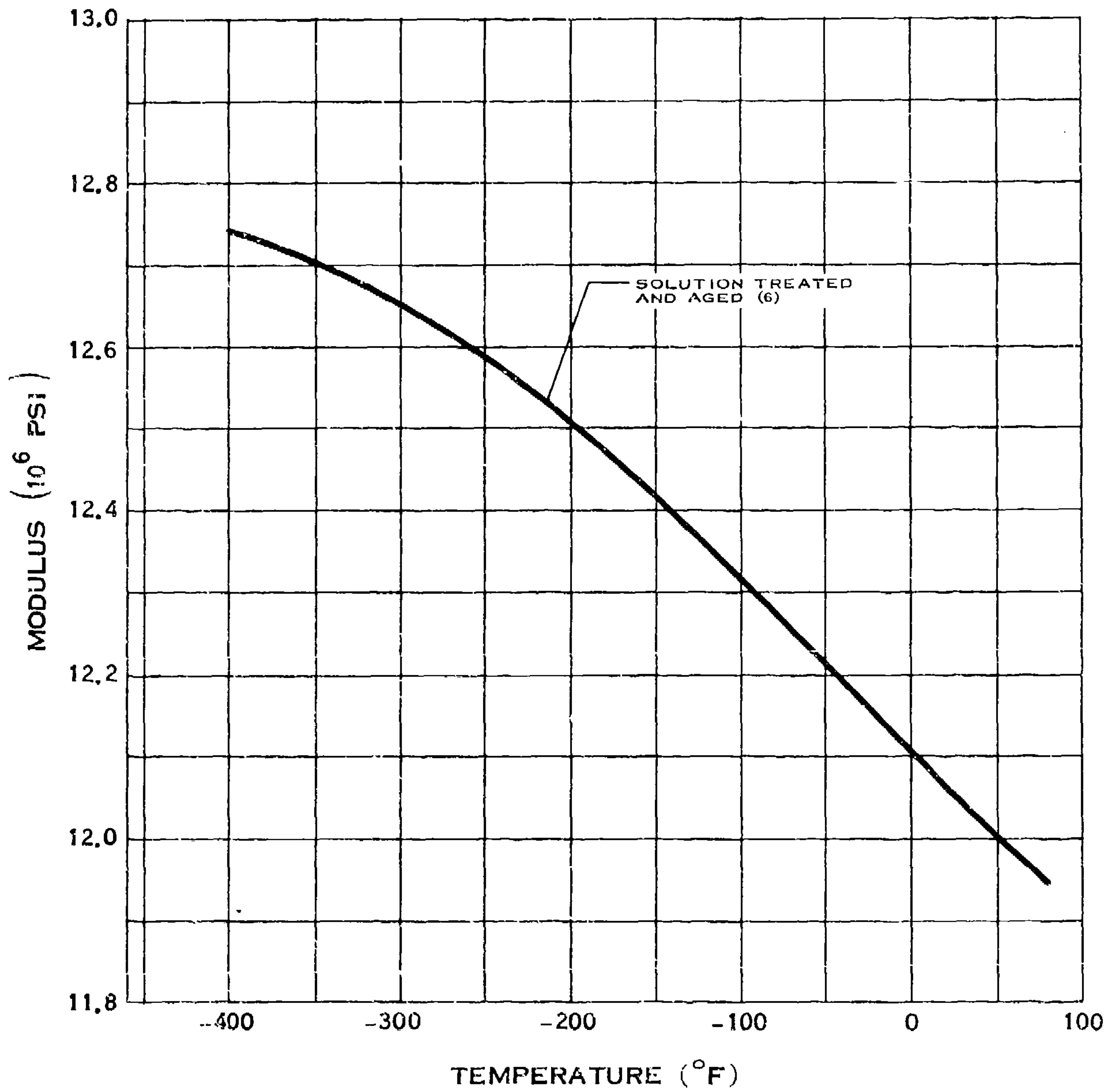
MODULUS OF ELASTICITY OF INCONEL X



IMPACT STRENGTH OF INCONEL X

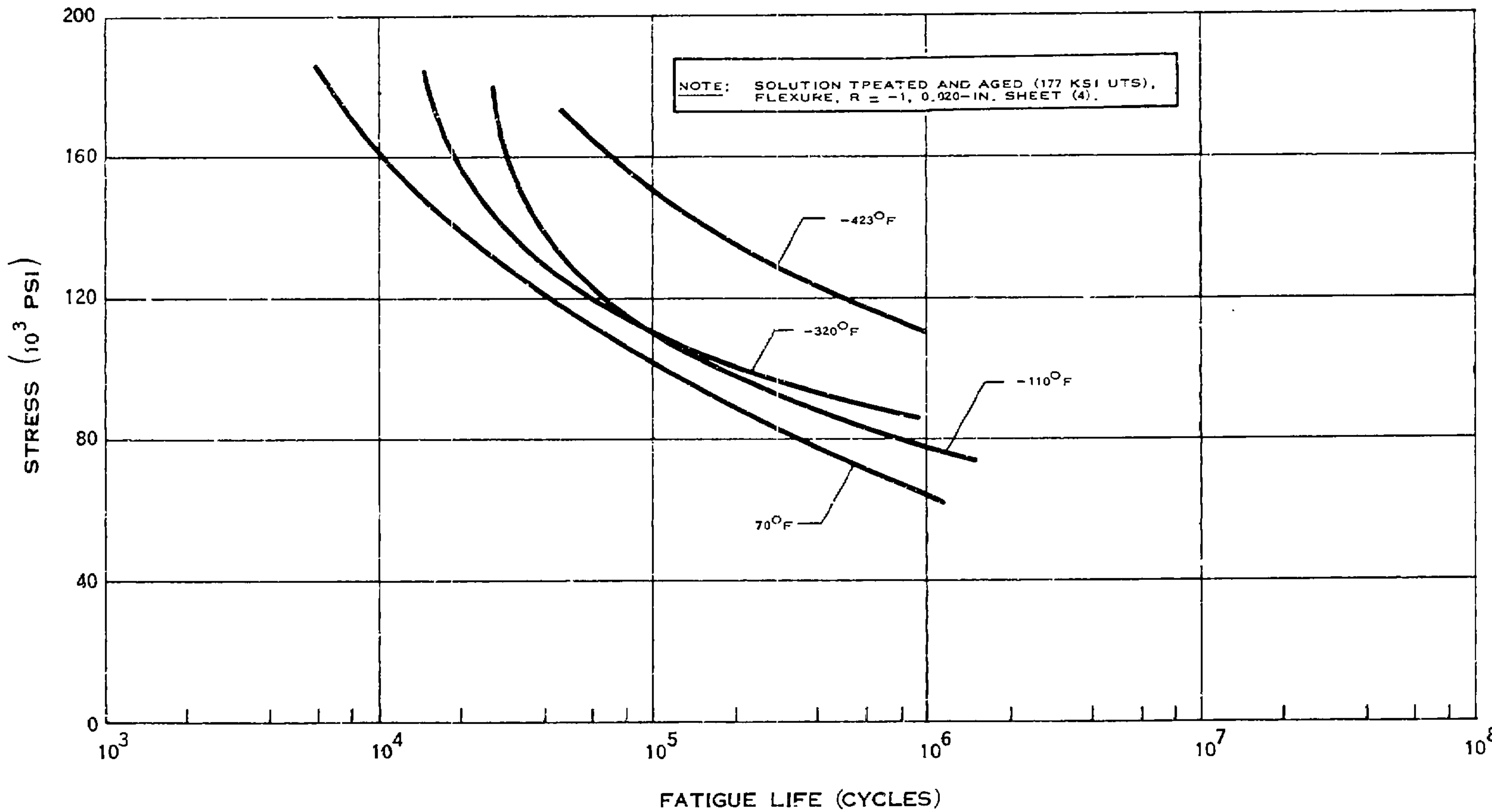
(7-64)

D.3.ℓ



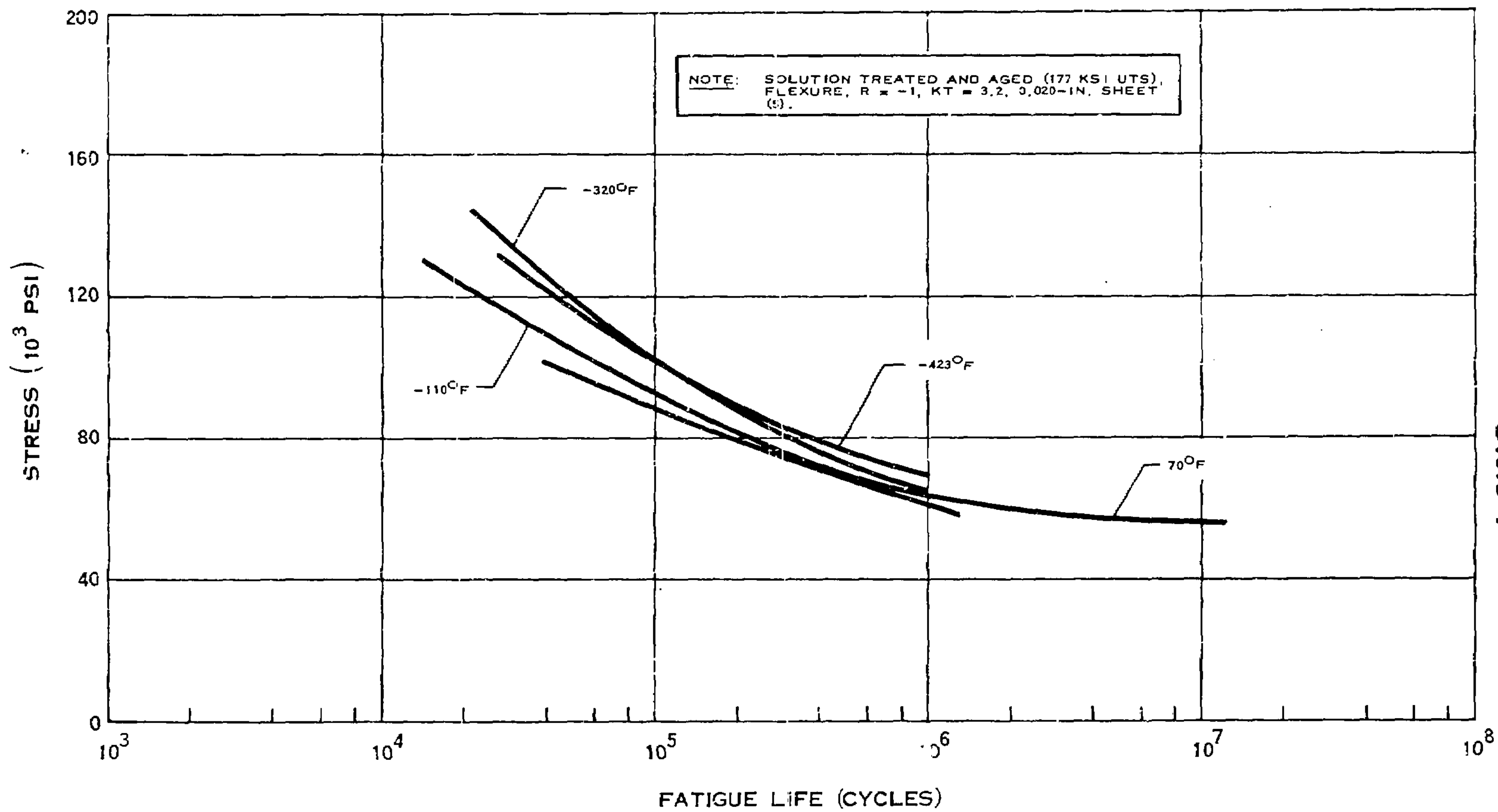
MODULUS OF RIGIDITY OF INCONEL X

(7-64)



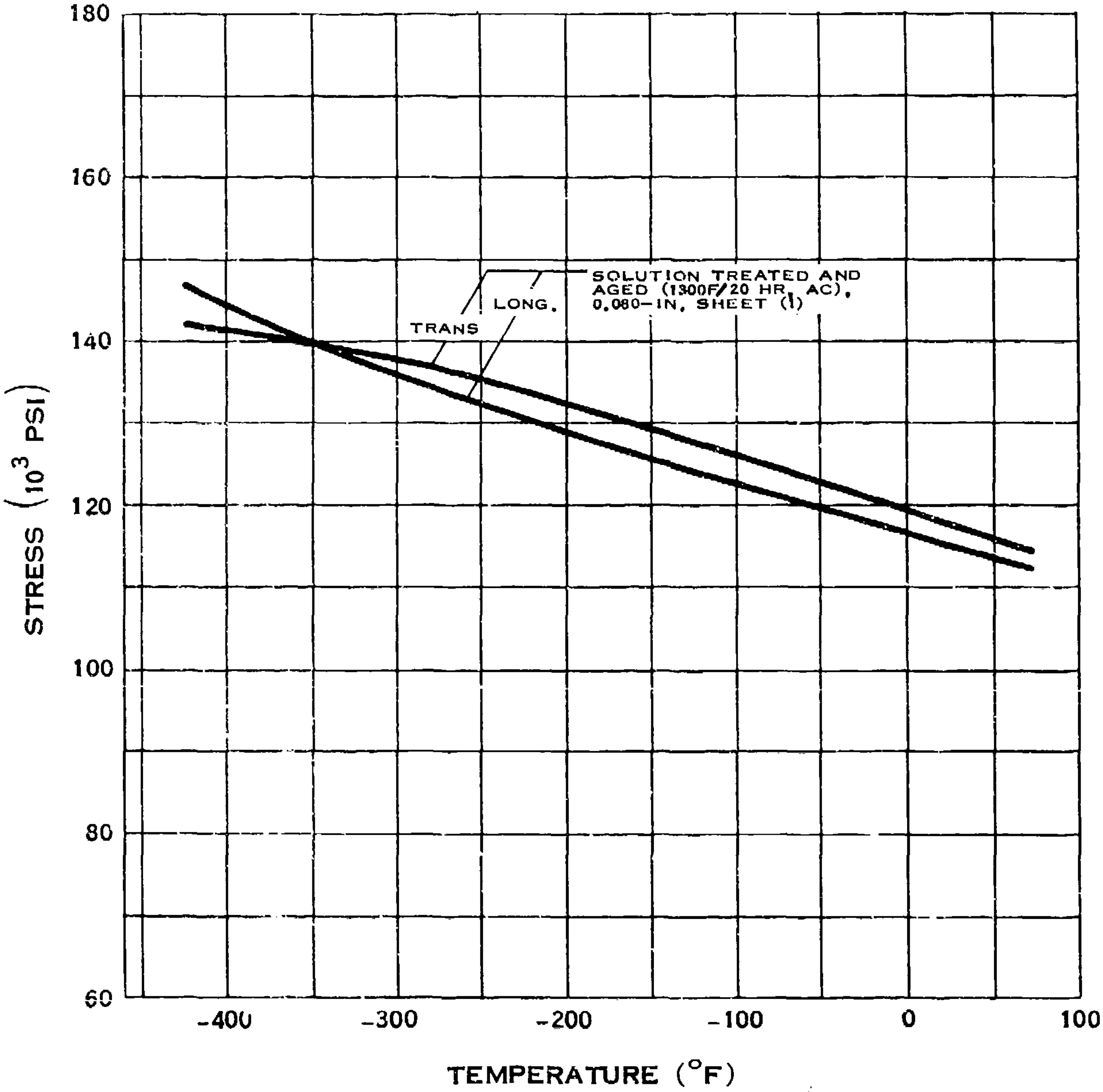
FATIGUE STRENGTH OF INCONEL X

(7−64)

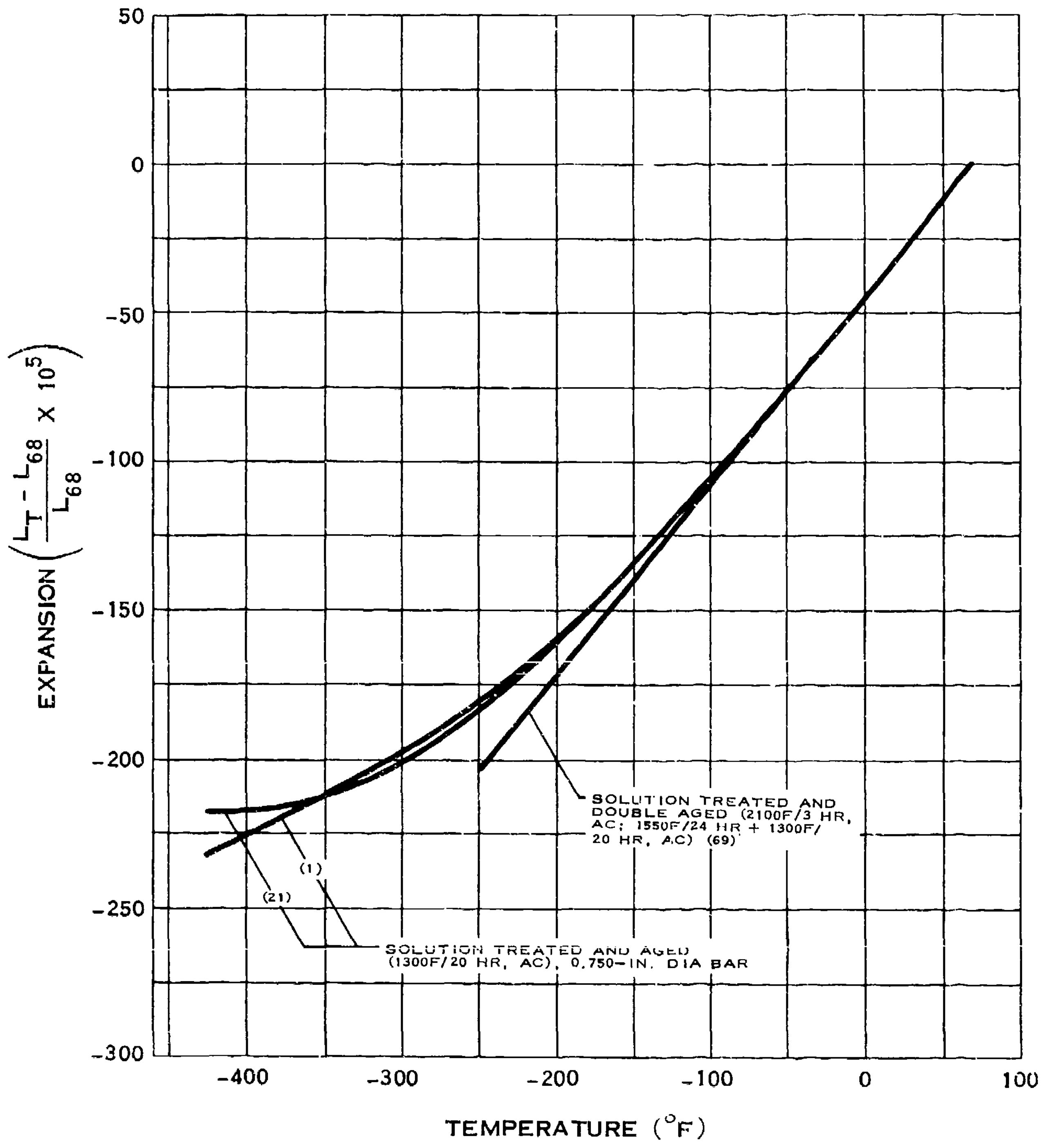


NOTCH FATIGUE STRENGTH OF INCONEL X

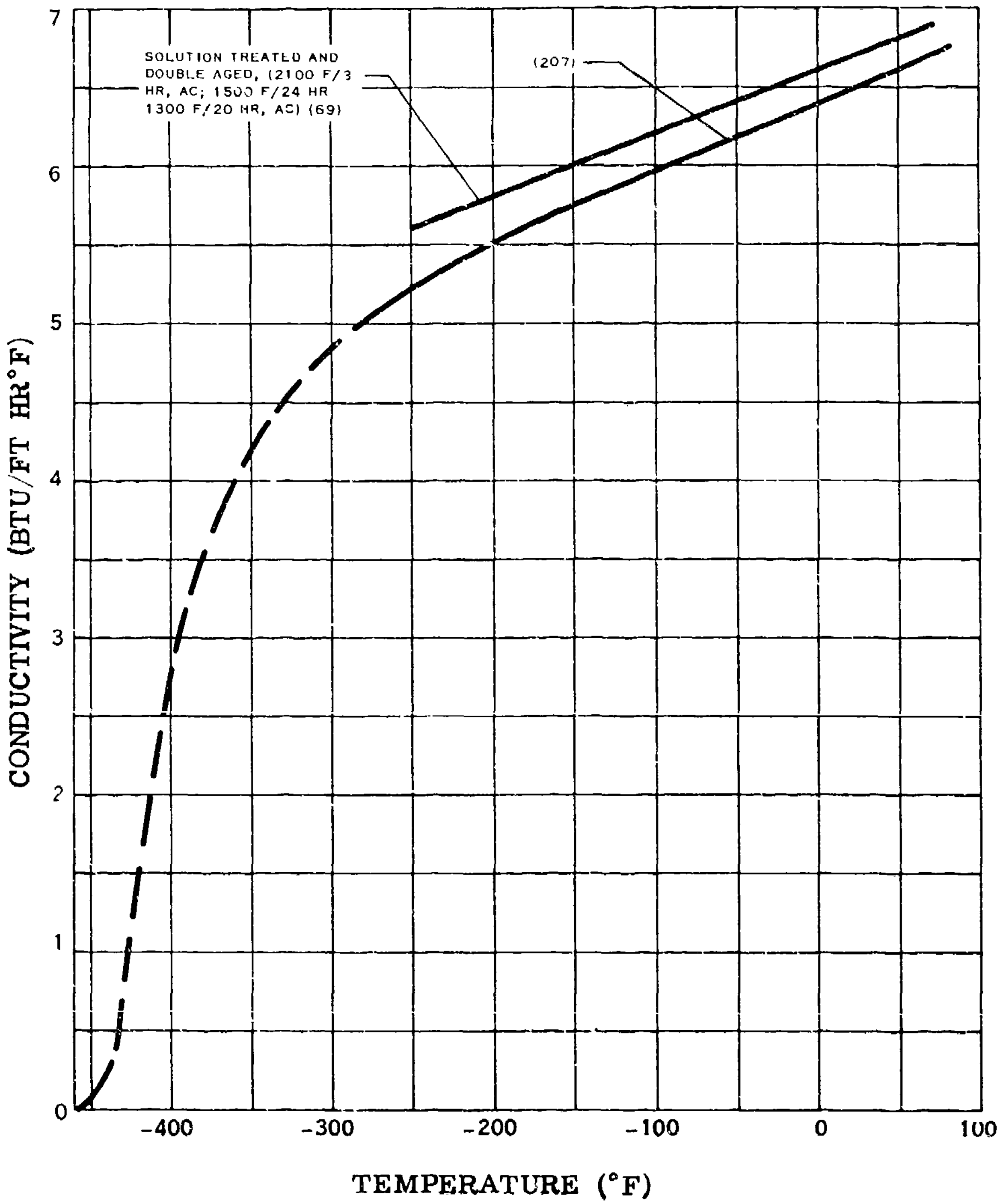
(7-64)



SHEAR STRENGTH OF INCONEL X

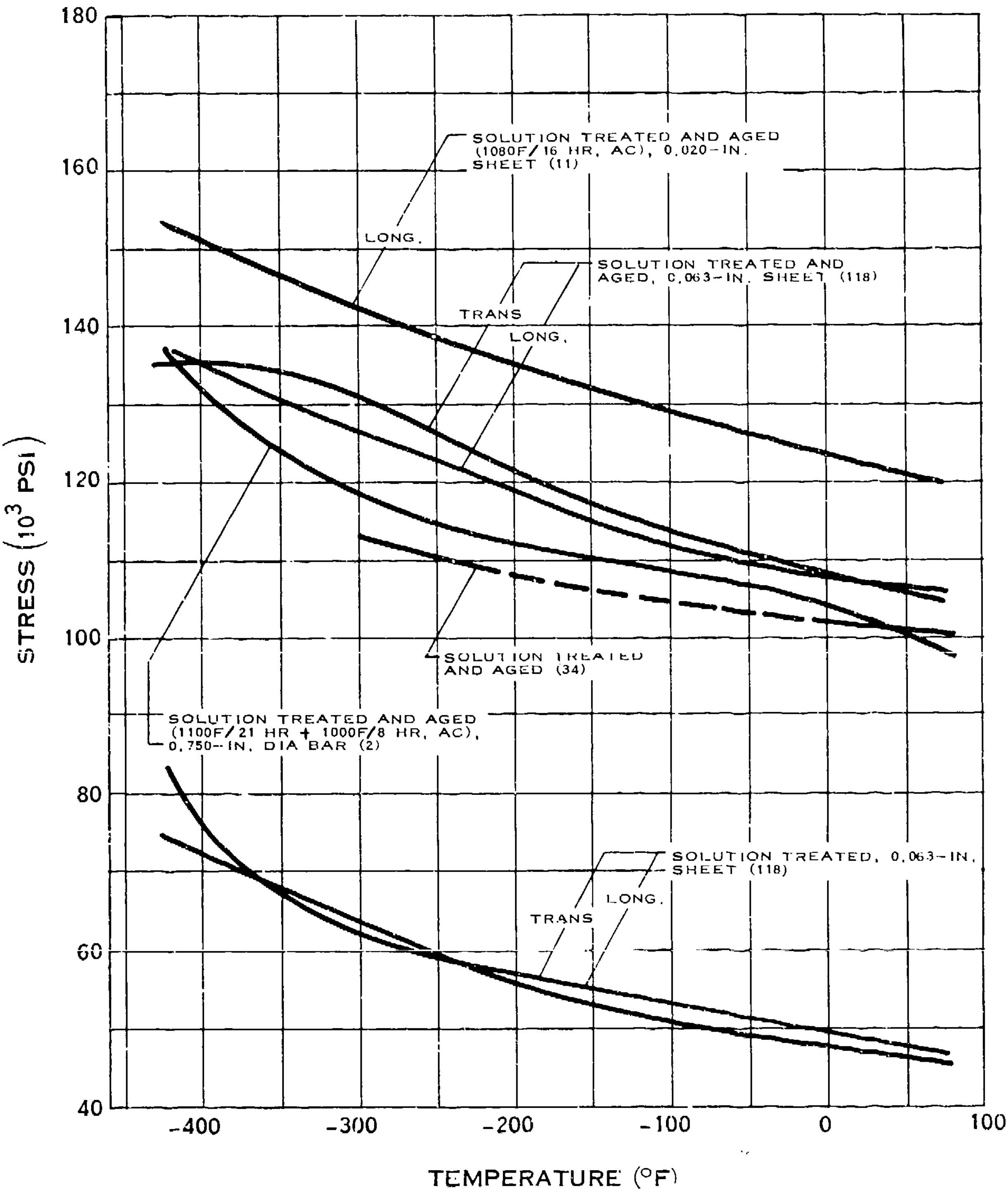


THERMAL EXPANSION OF INCONEL X



THERMAL CONDUCTIVITY OF INCONEL X

(6-68)



YIELD STRENGTH OF K MONEL

(7-65)

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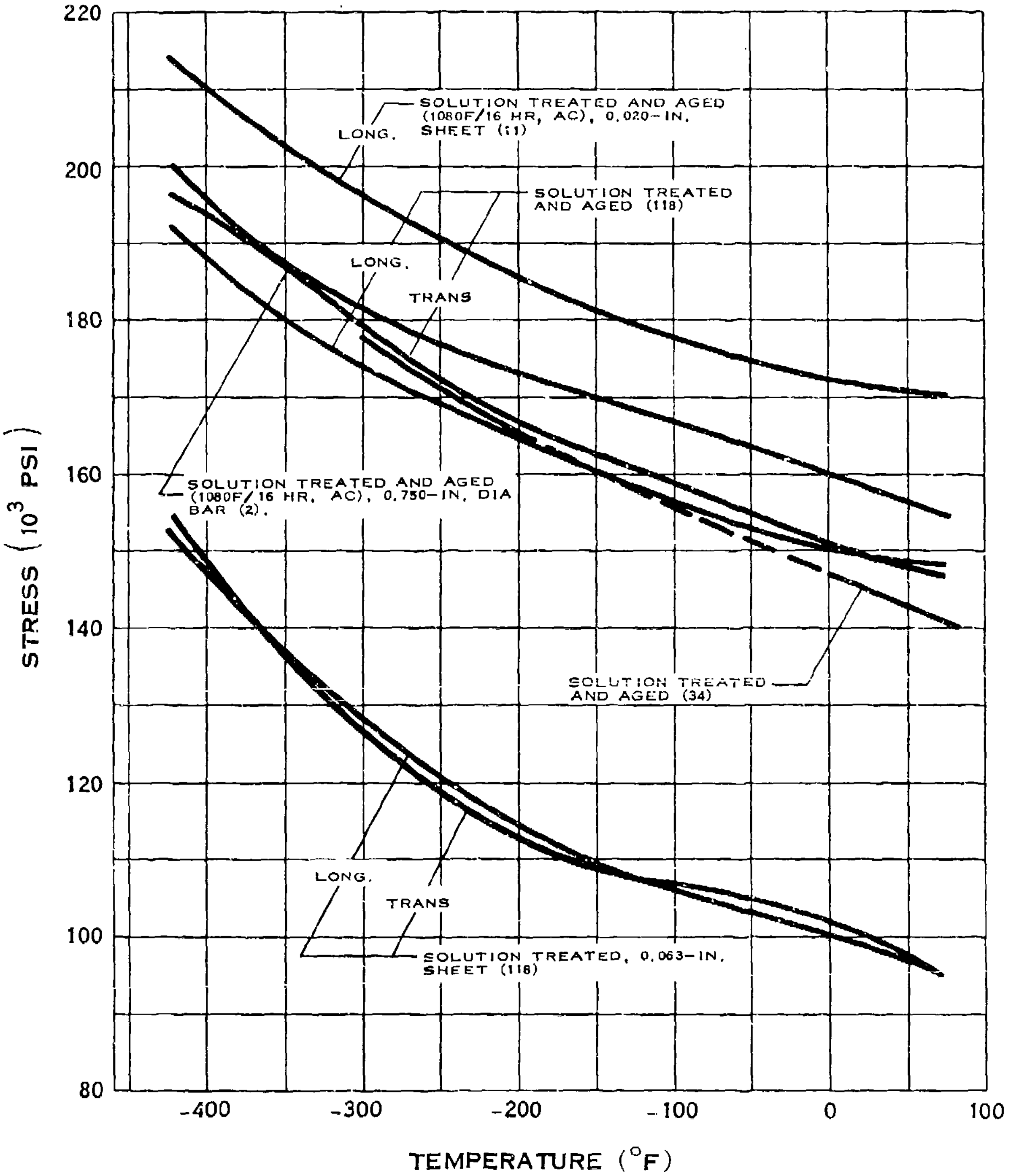
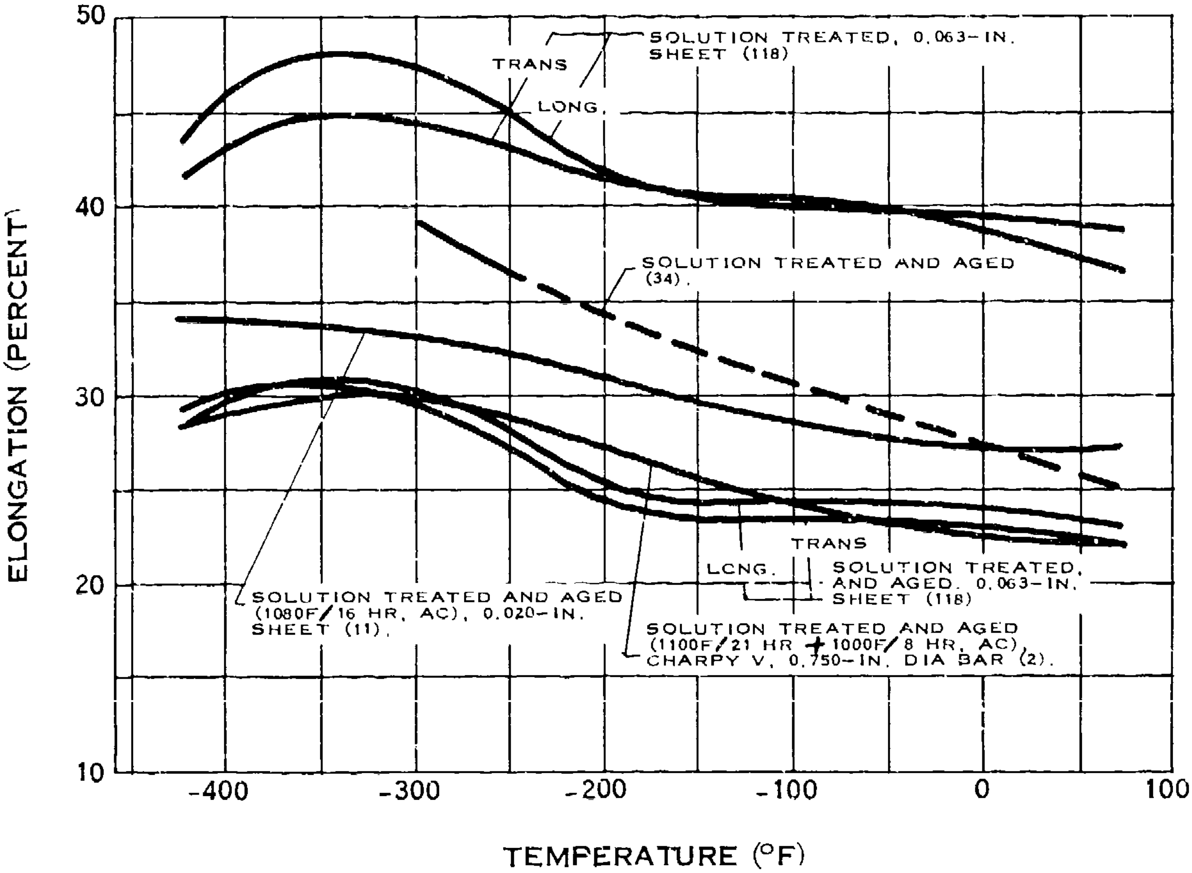


TENSILE STRENGTH OF K MONEL

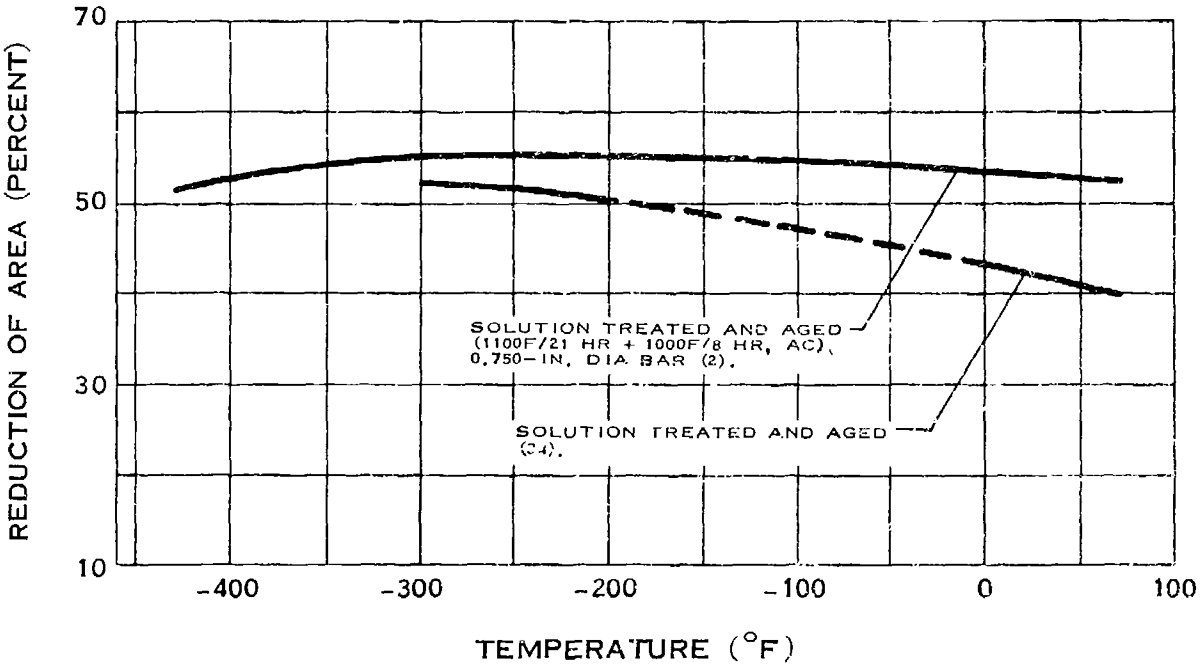
(7-65)



ELONGATION OF K MONEL

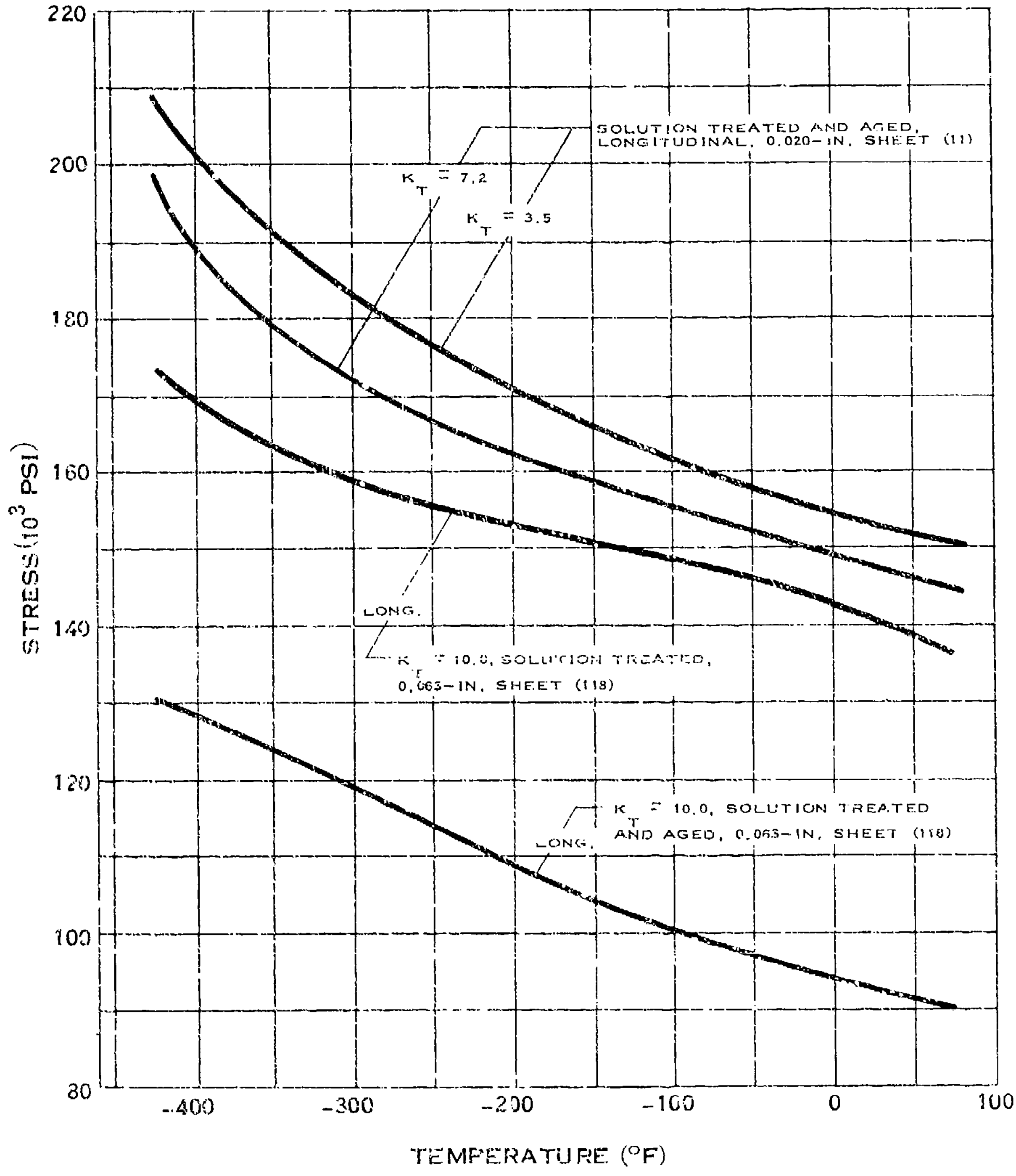
(7-65)

D.4.d



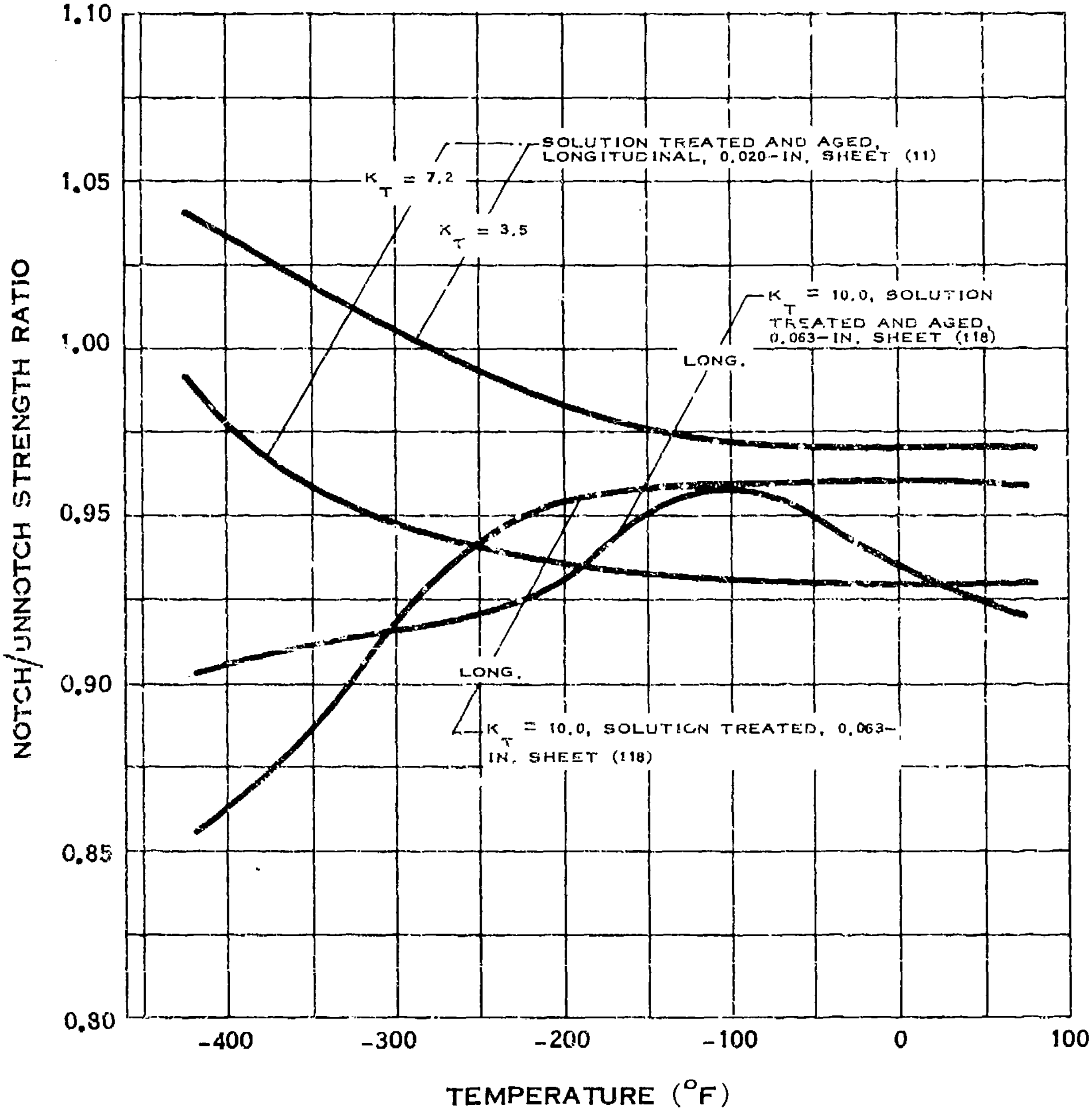
REDUCTION OF AREA OF K MONEL

(7-65)



NOTCH TENSILE STRENGTH OF K MONEL

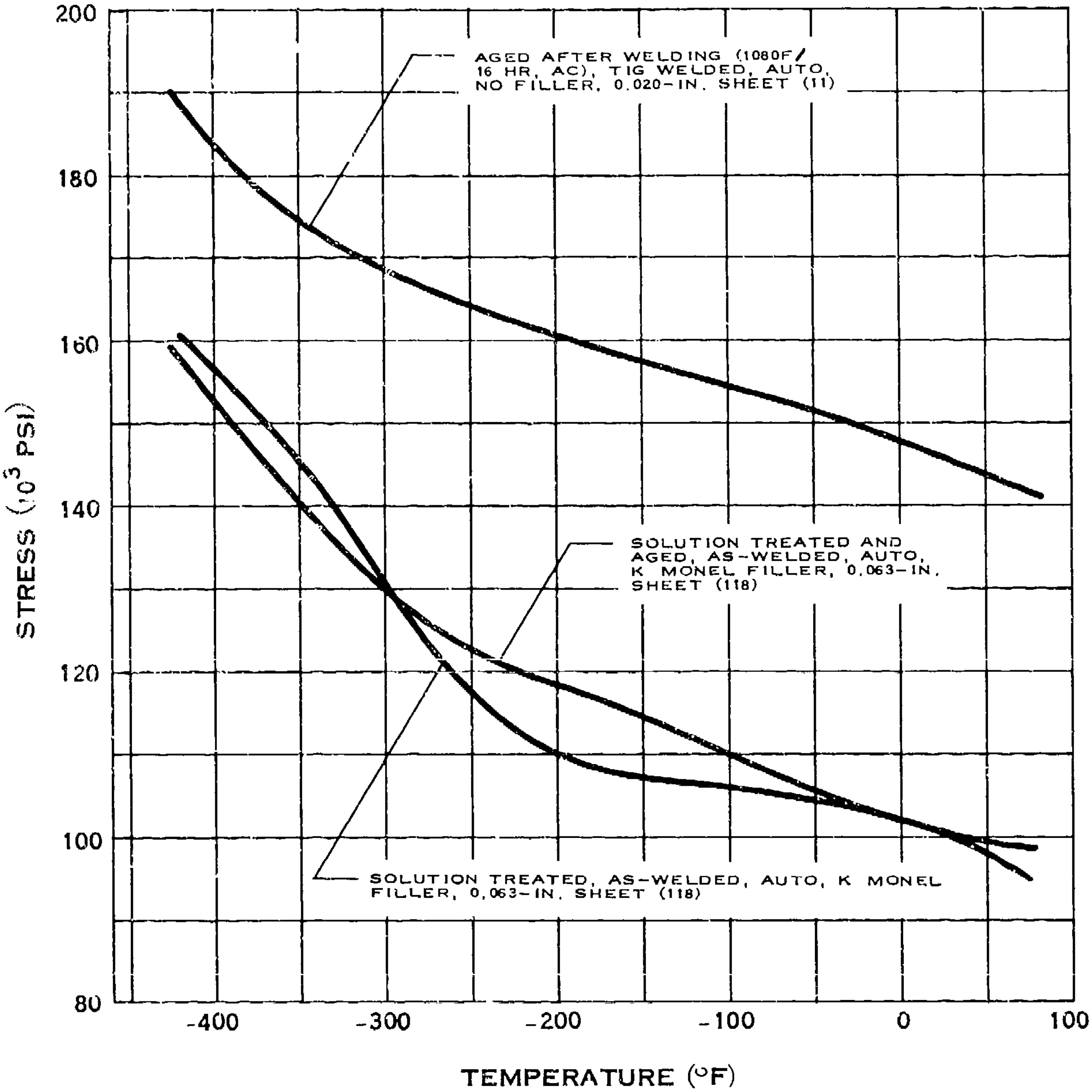
(7-65)



NOTCH STRENGTH RATIO OF K MONEL

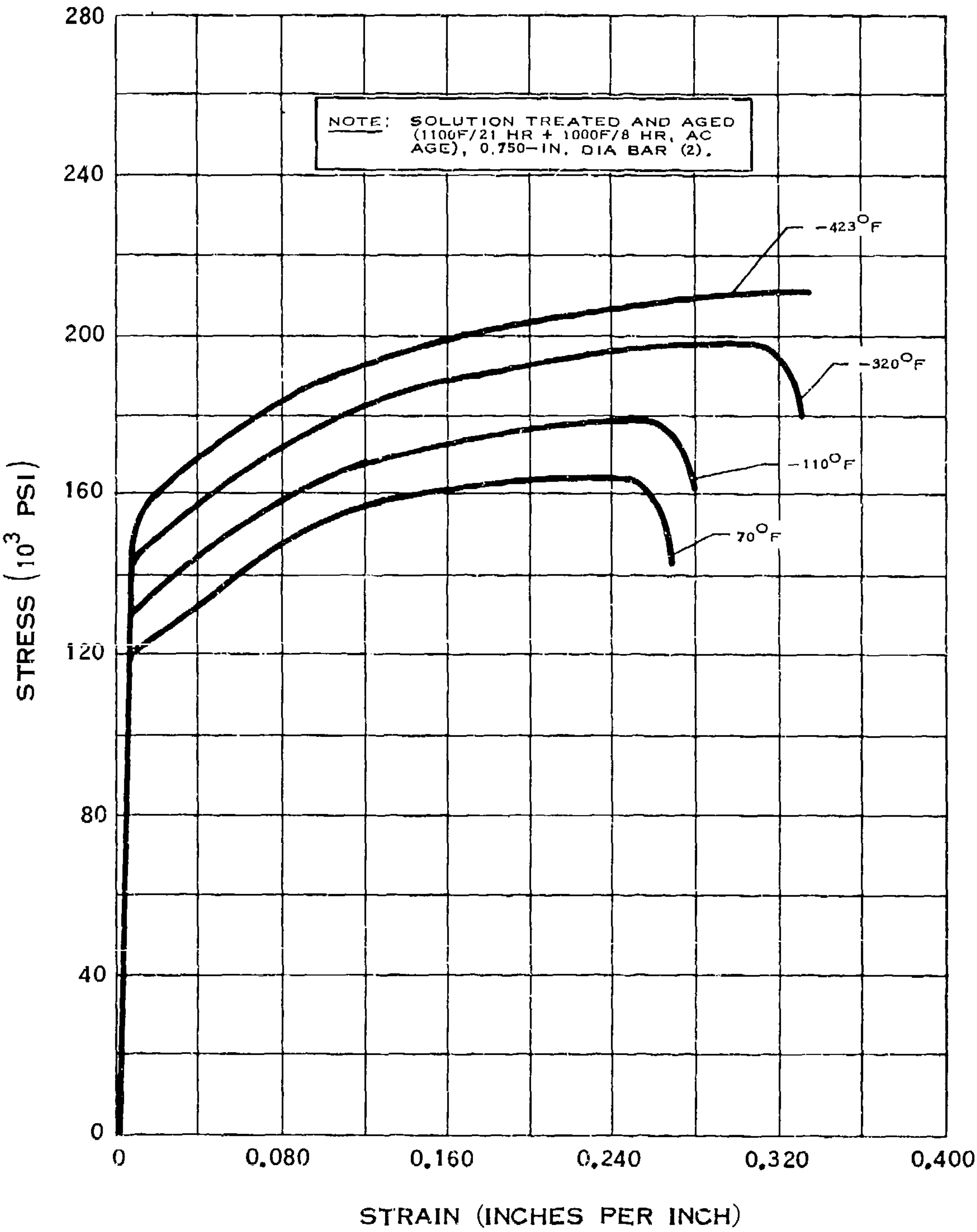
(7-63)

D.4.g



WELD TENSILE STRENGTH OF K MONEL

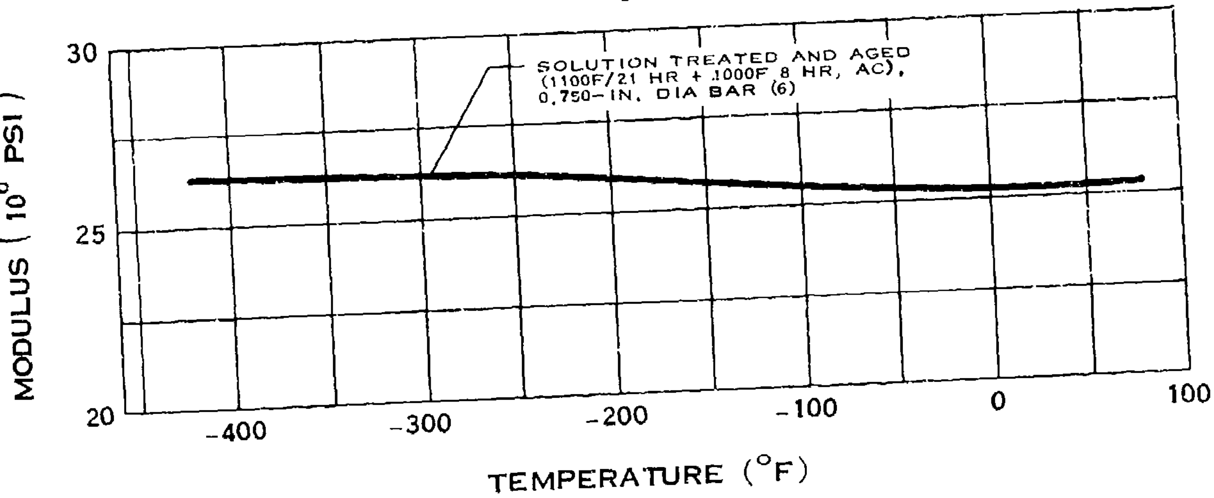
(7-65)



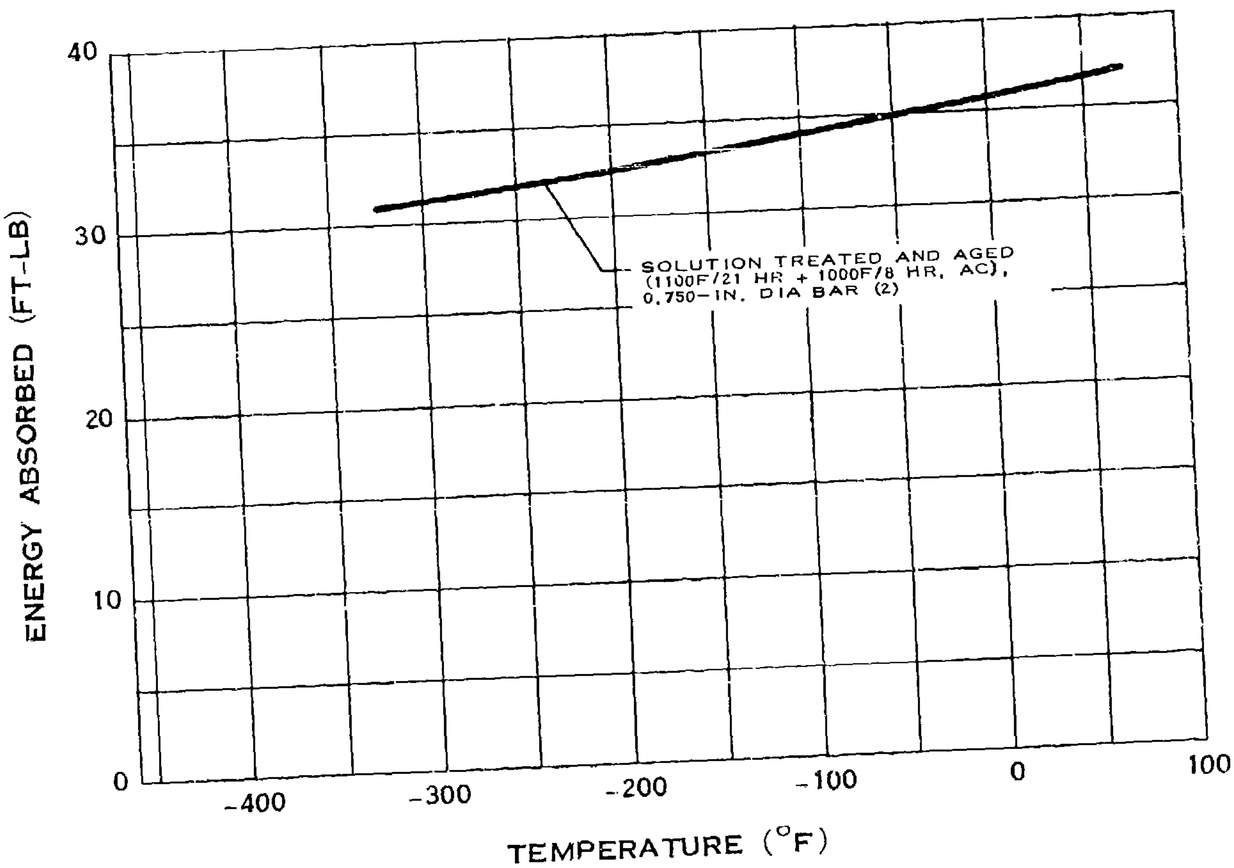
STRESS-STRAIN DIAGRAM FOR K MONEL

(7-64)

D.4.ij

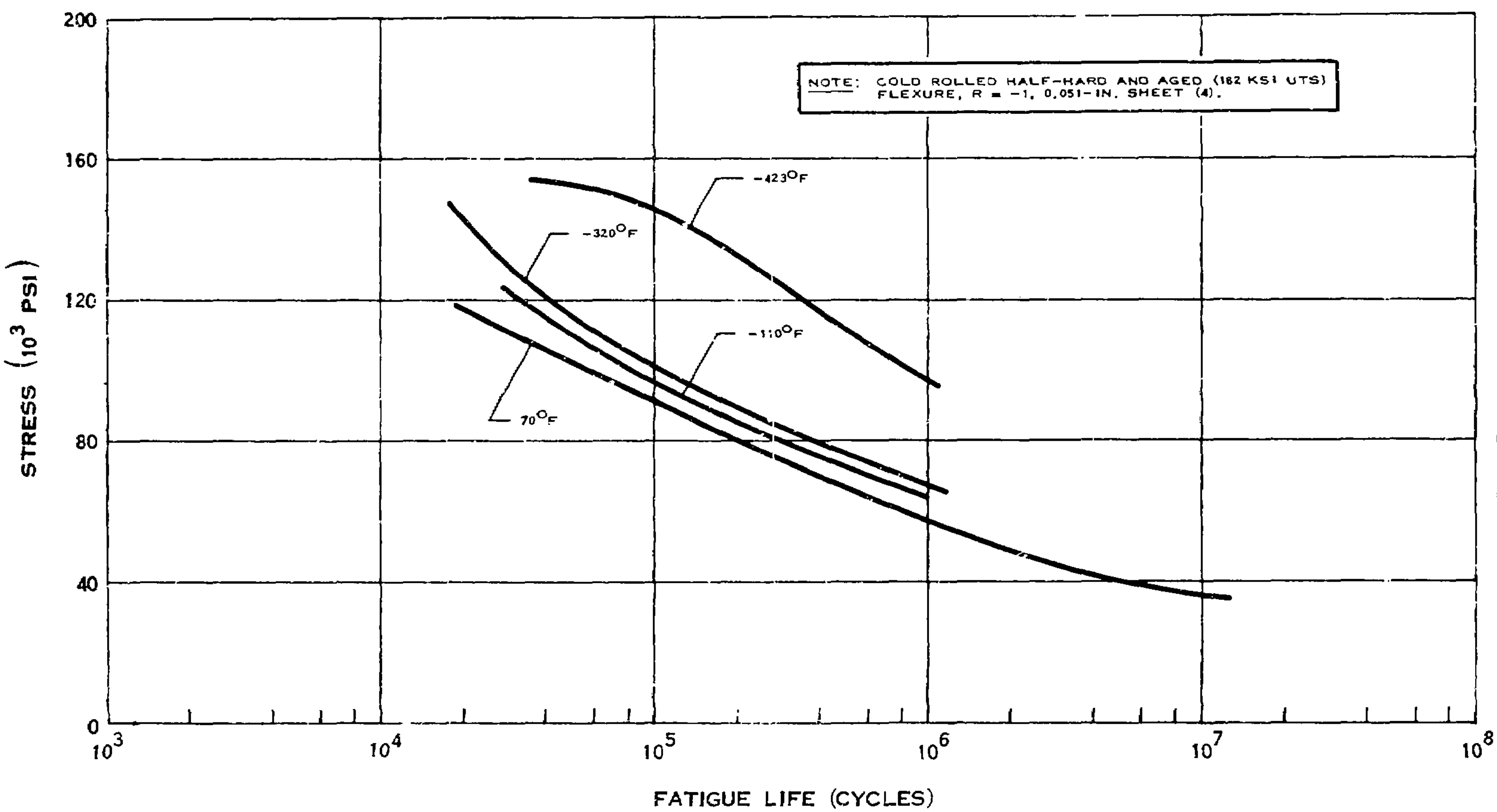


MODULUS OF ELASTICITY OF K MONEL



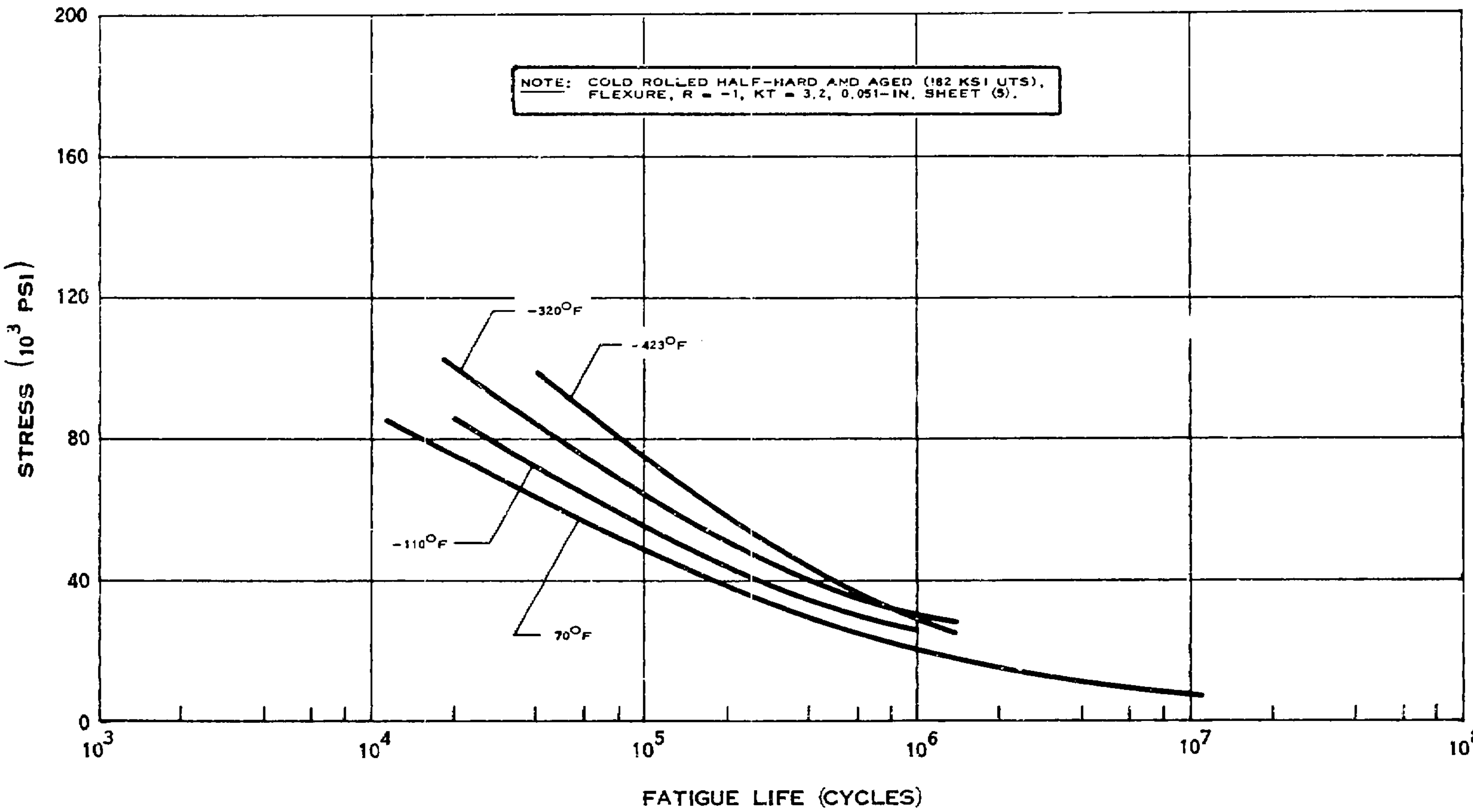
IMPACT STRENGTH OF K MONEL

(7-64)

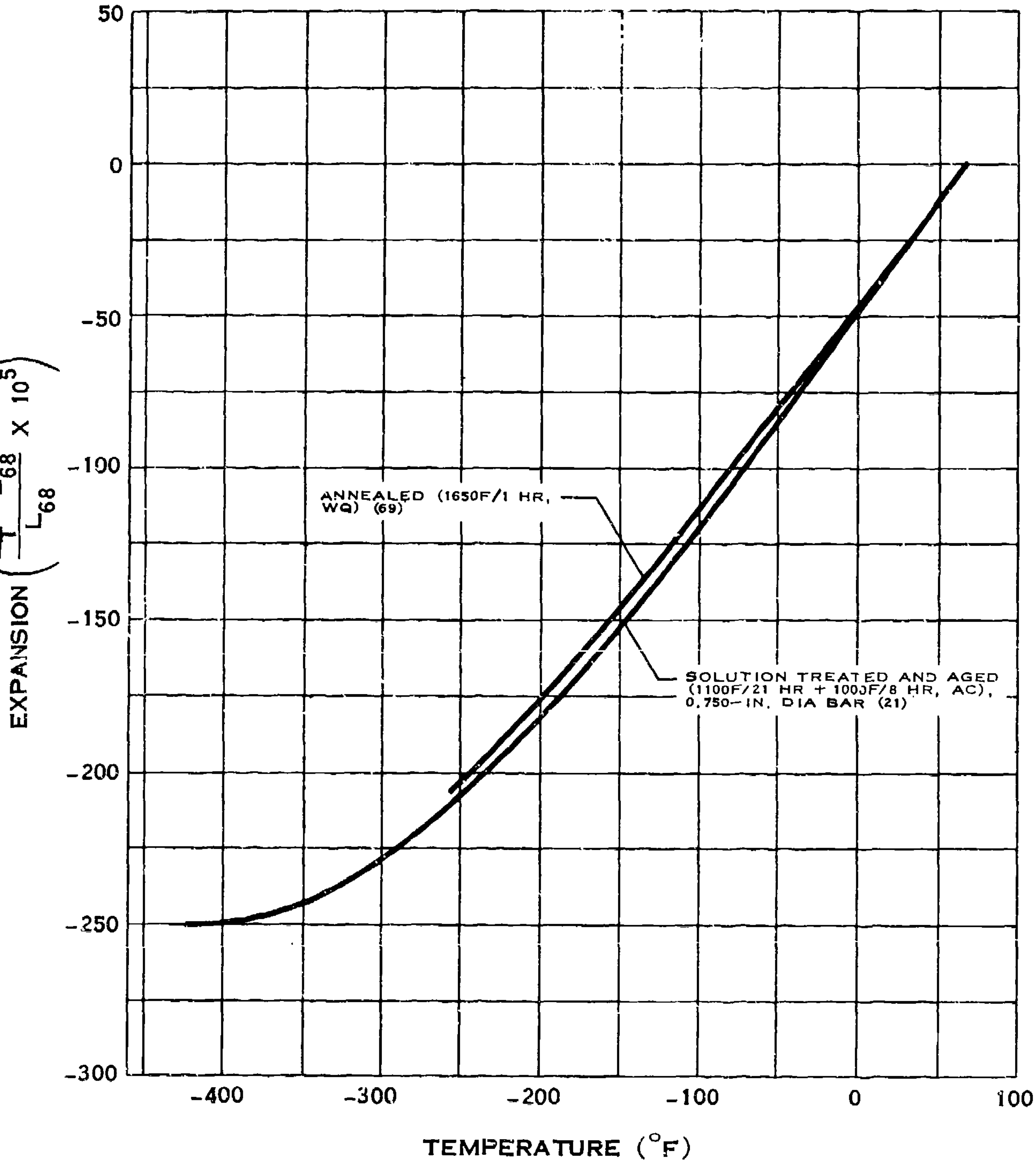


FATIGUE STRENGTH OF K MONEL

(7-64)



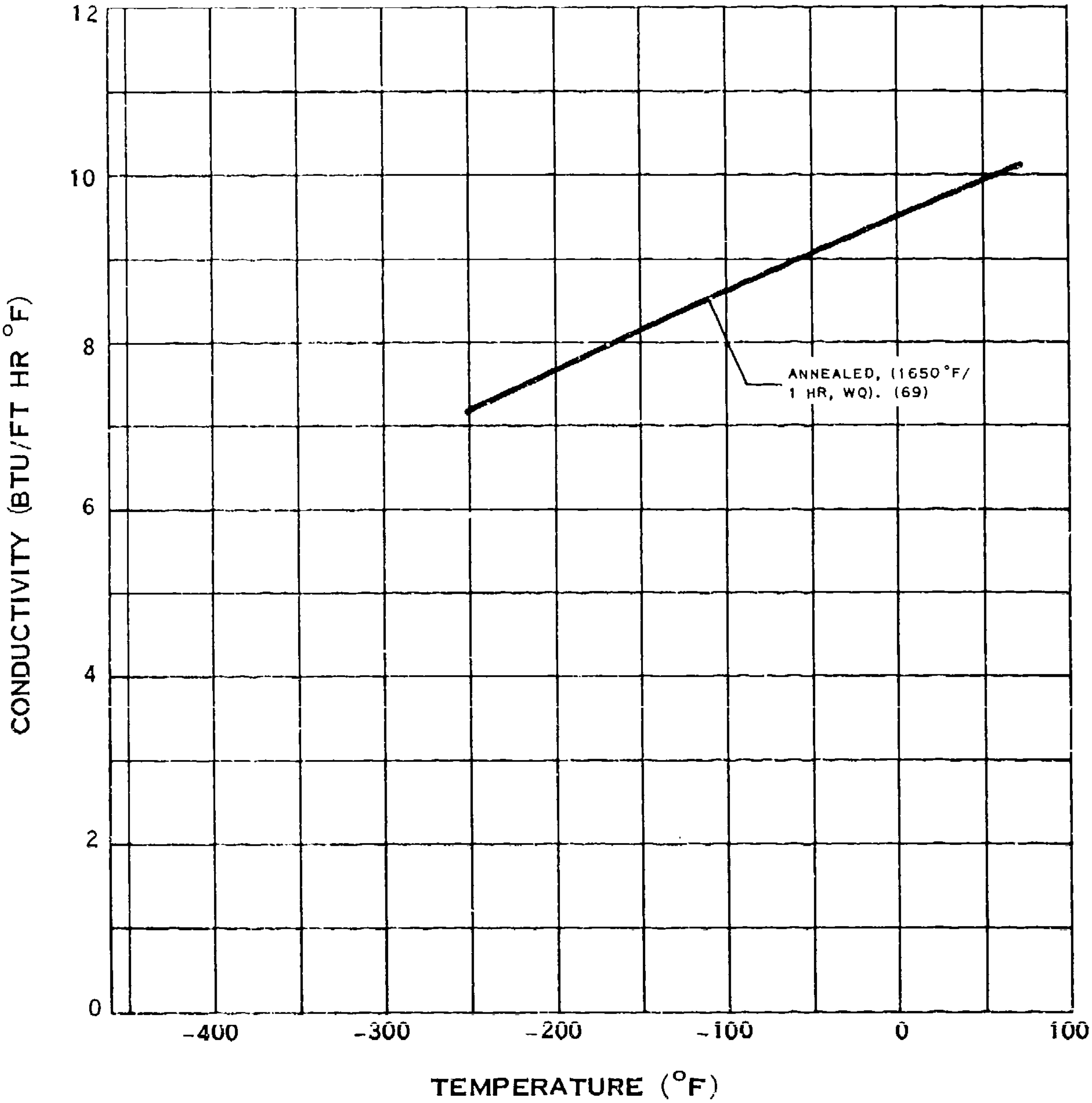
NOTCH FATIGUE STRENGTH OF K MONEL



THERMAL EXPANSION OF K MONEL

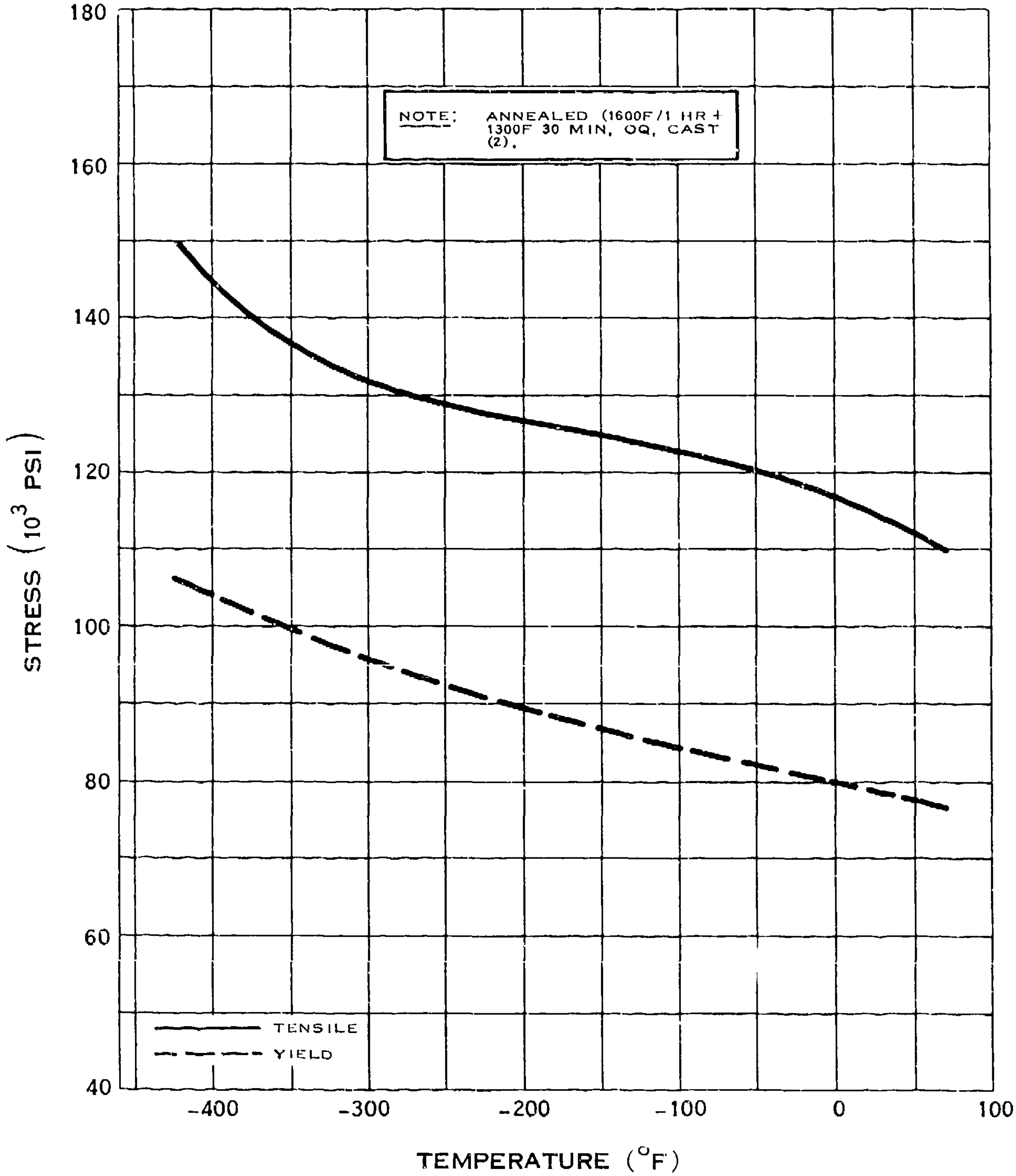
(7-64)

D.4.v



THERMAL CONDUCTIVITY OF K MONEL

(6-68)



STRENGTH OF S MONEL

(7-64)

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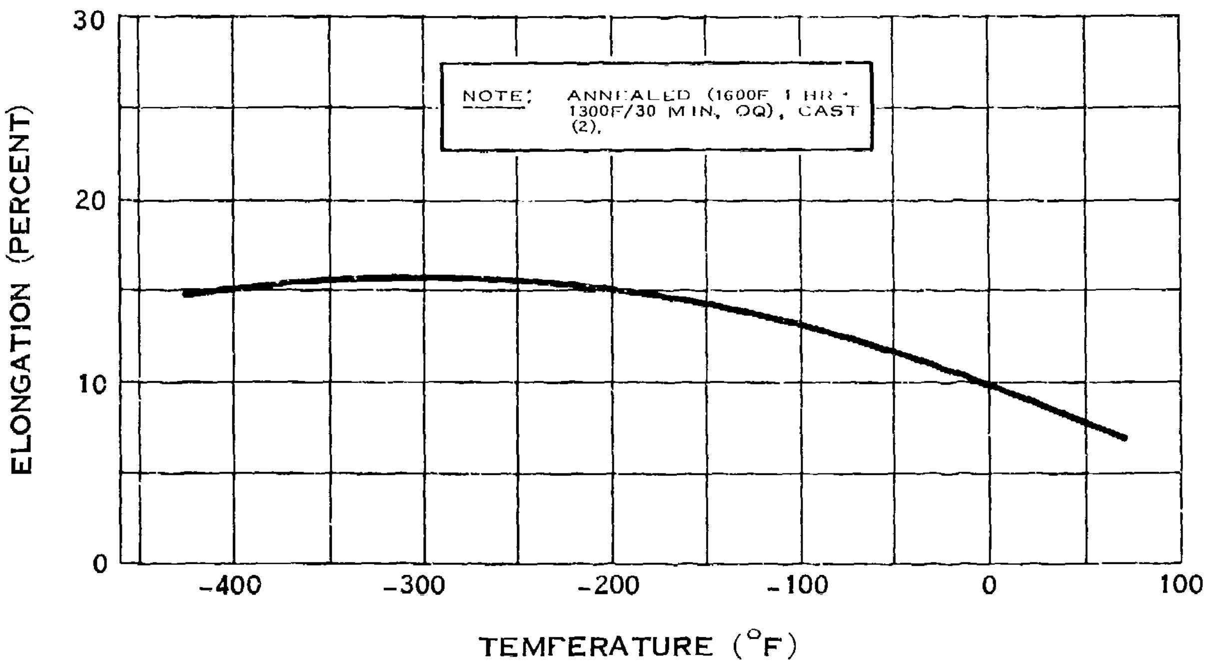
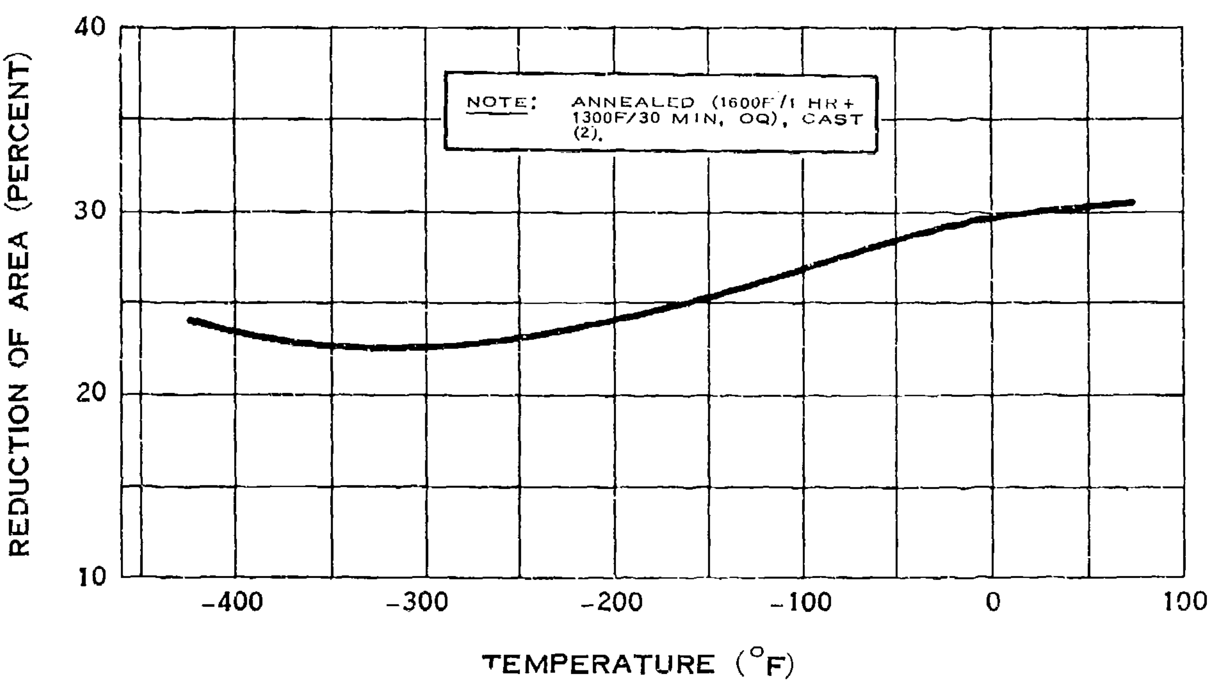


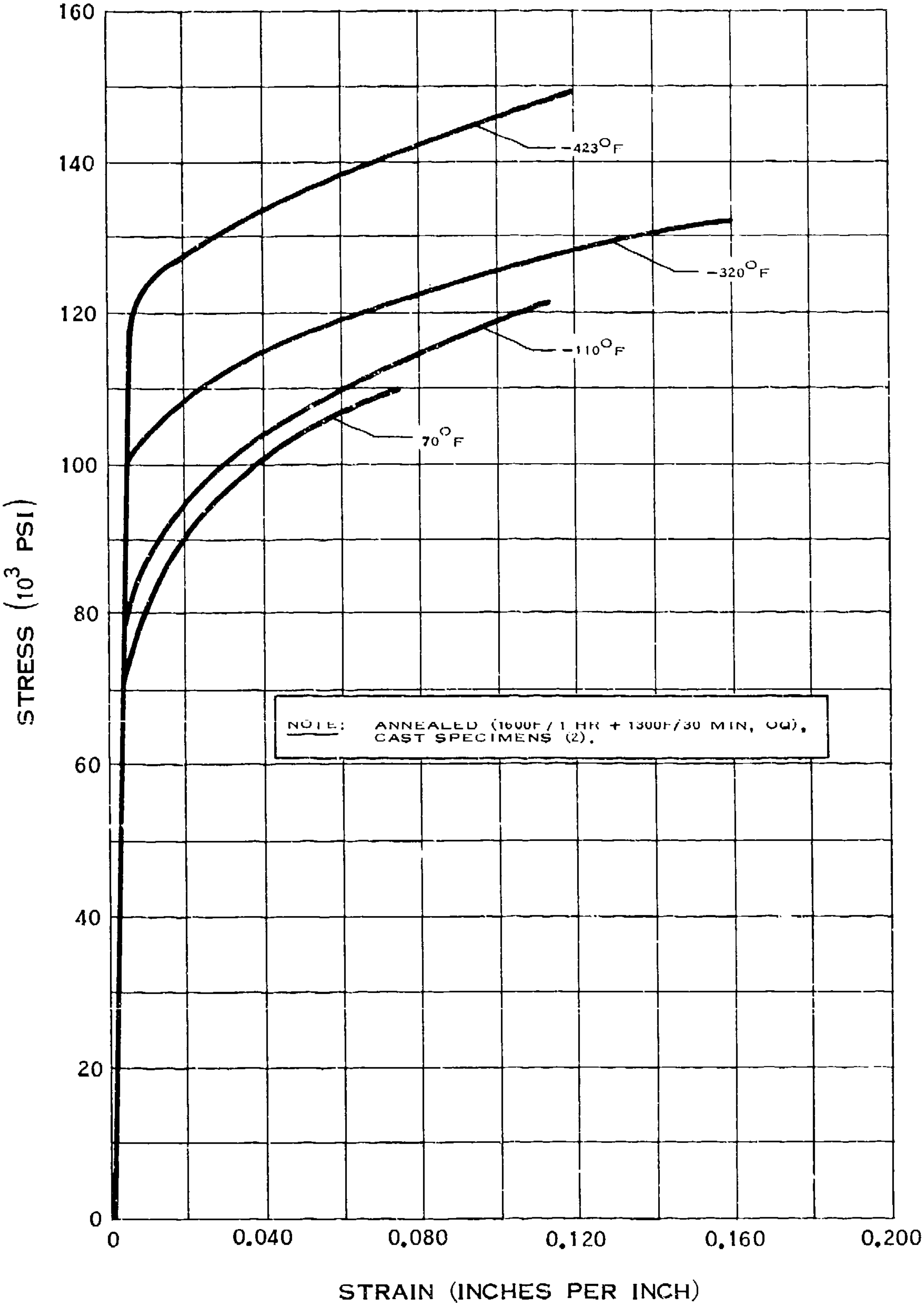
ELONGATION OF S MONEL



REDUCTION OF AREA OF S MONEL

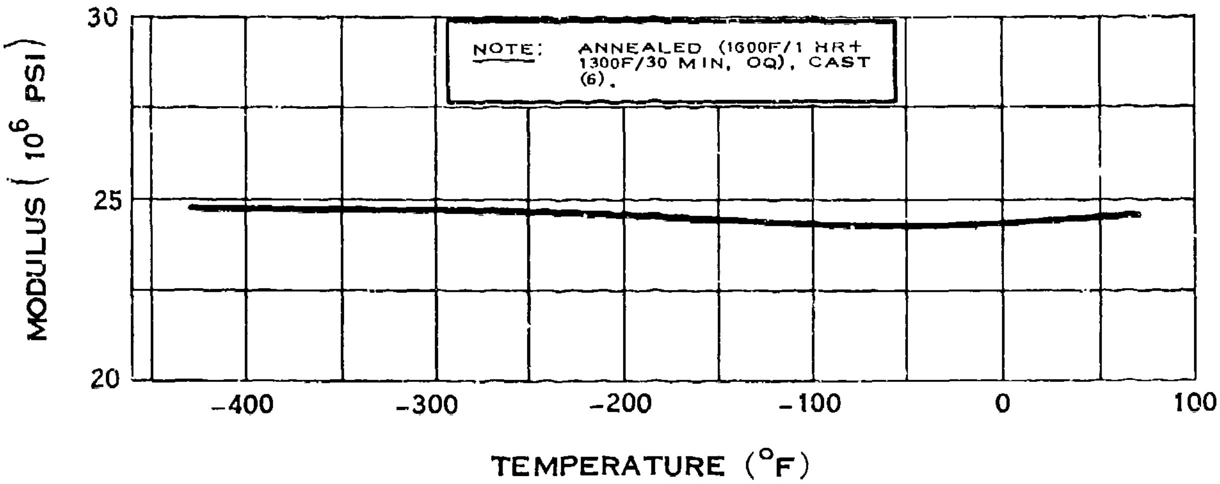
(7-64)

D.5.h

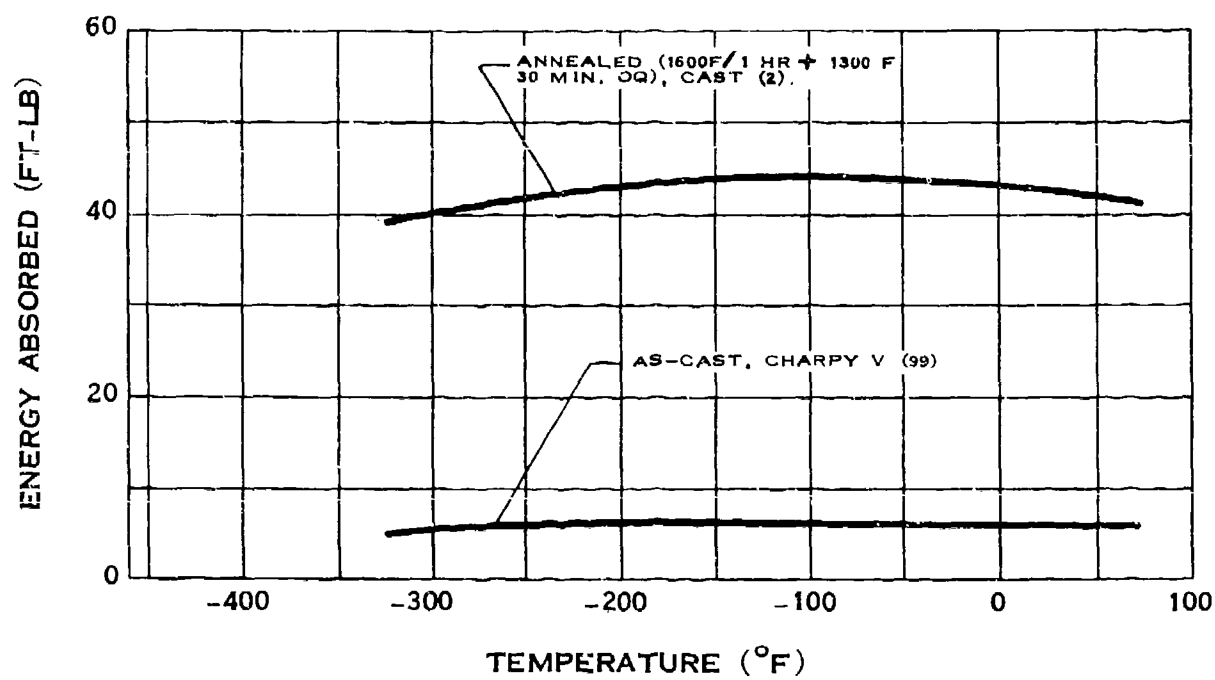


STRESS-STRAIN DIAGRAM FOR S MONEL

(7–64)



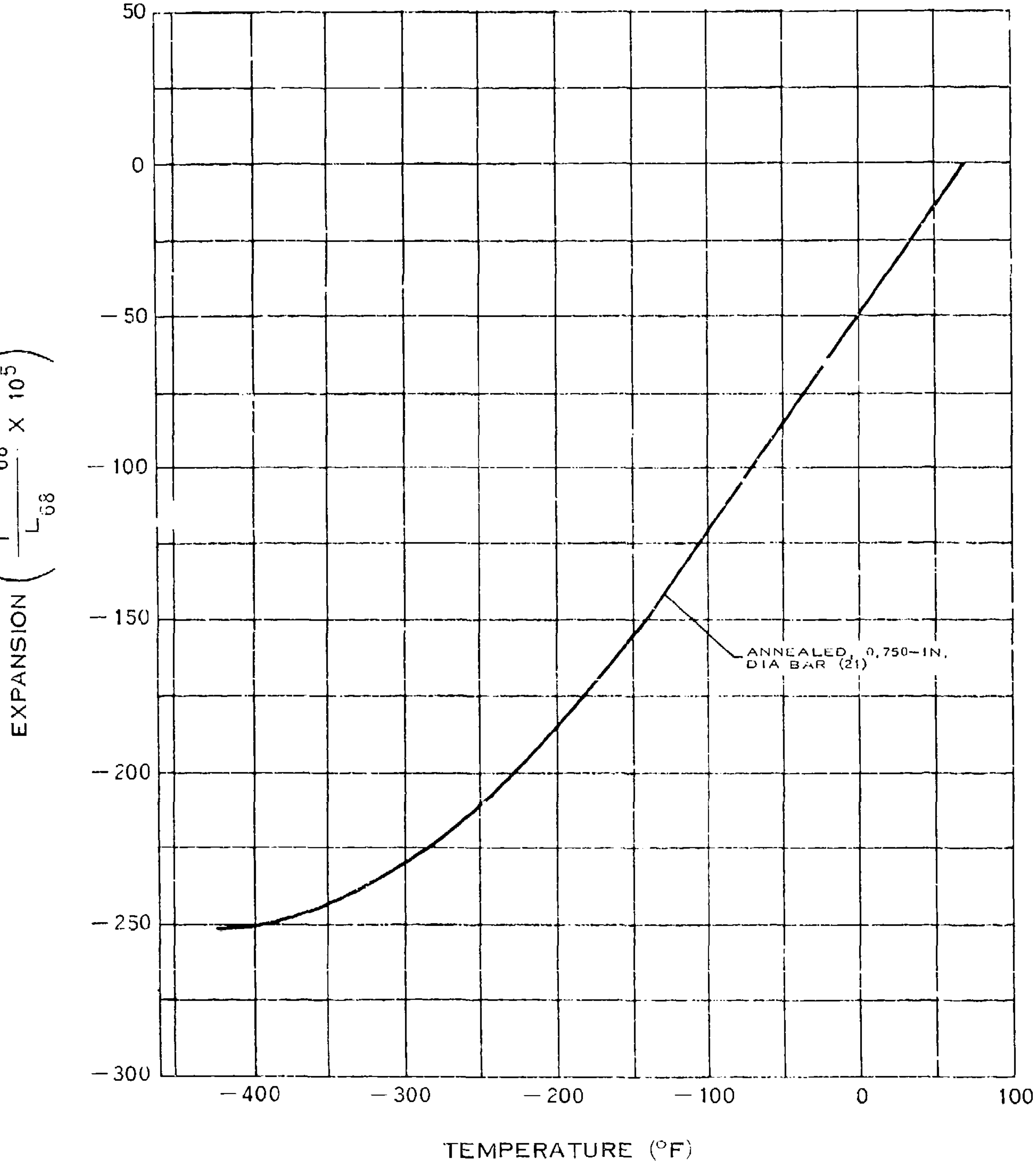
MODULUS OF ELASTICITY OF S MONEL



IMPACT STRENGTH OF S MONEL

(7-65)

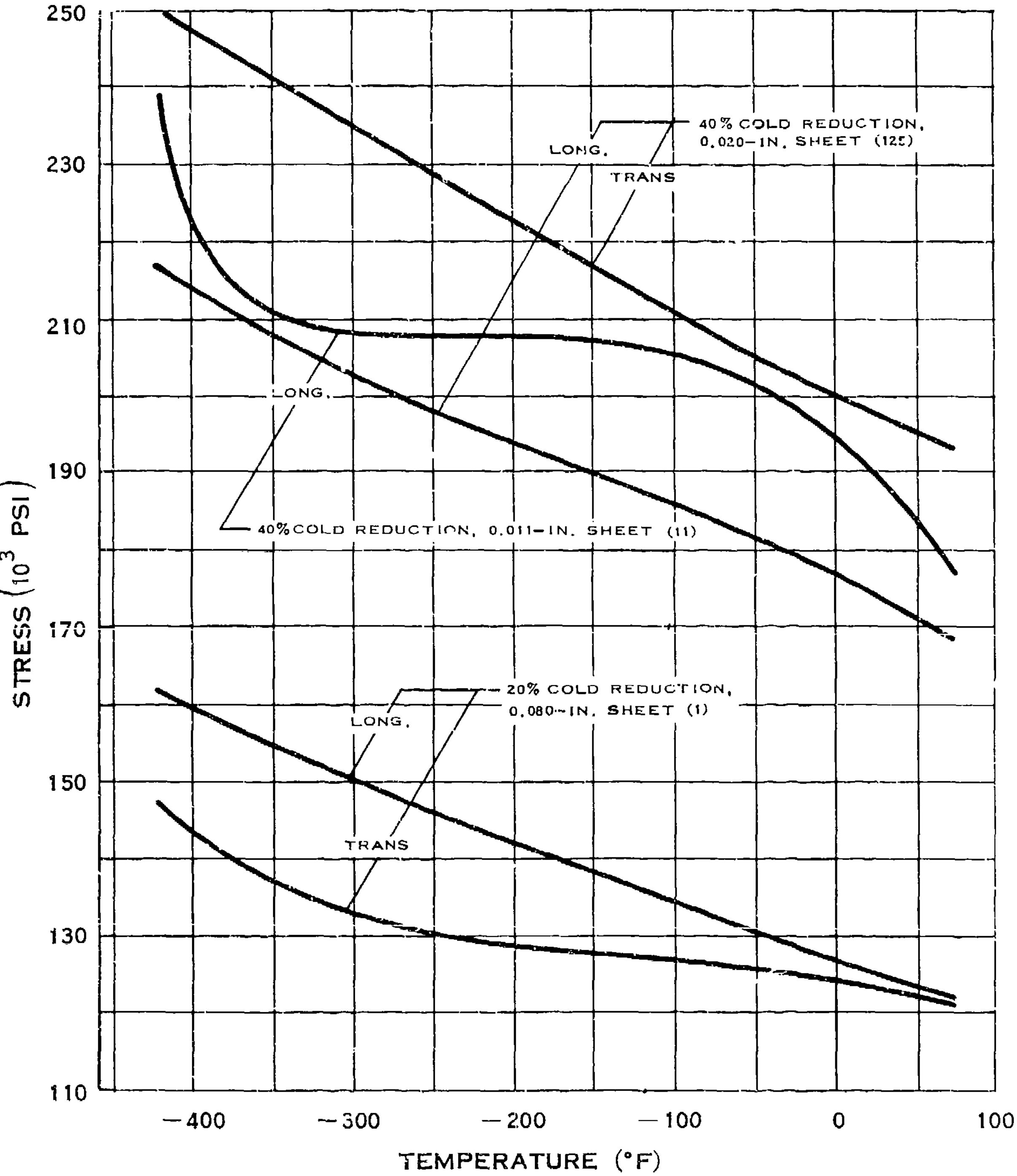
D.5.t



THERMAL EXPANSION OF S MONEL

(7-64)

D.6.a



(7-65)

YIELD STRENGTH OF HASTELLOY B

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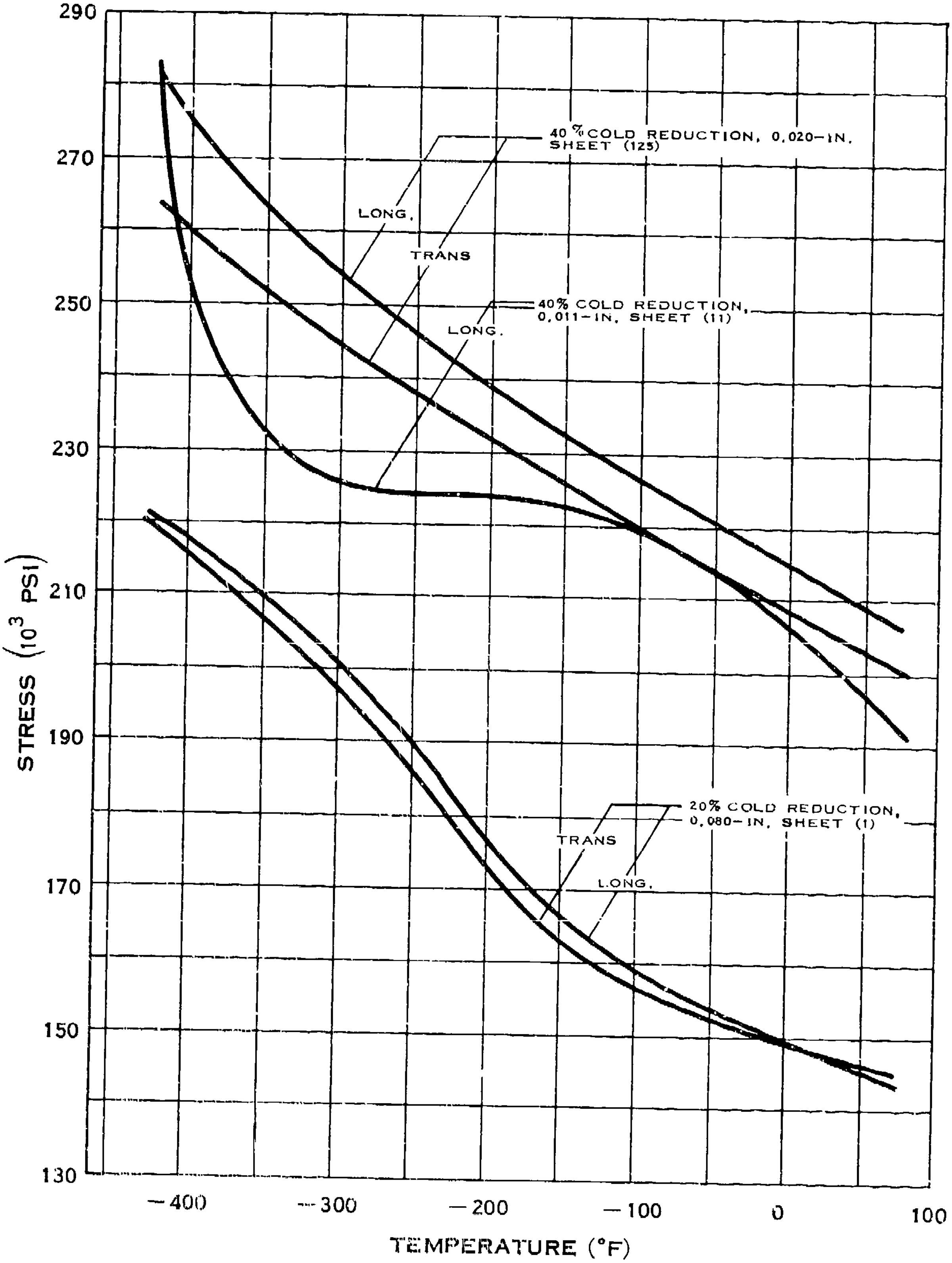
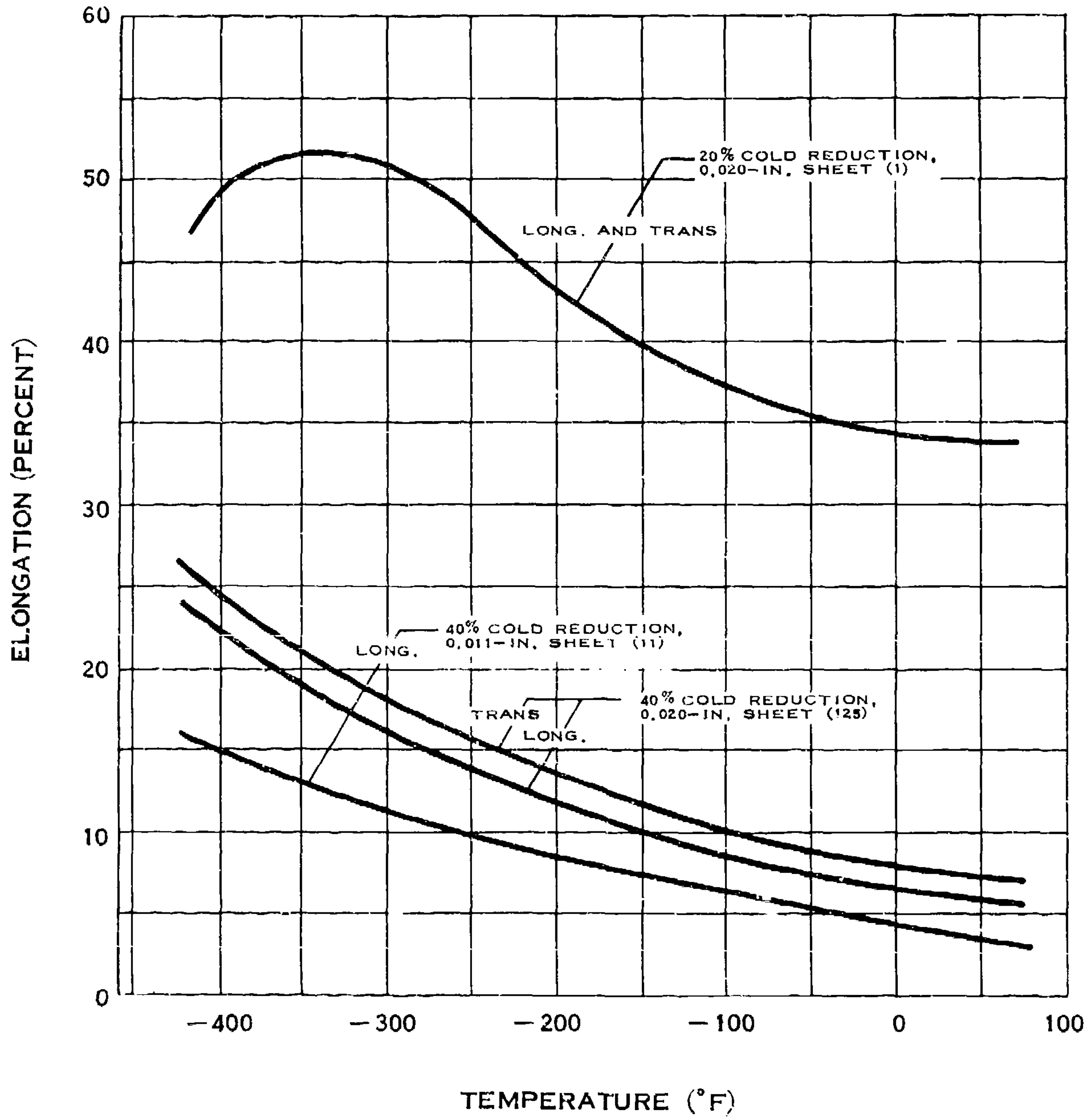
D.6.b



(7-65)

TENSILE STRENGTH OF HASTELLOY B

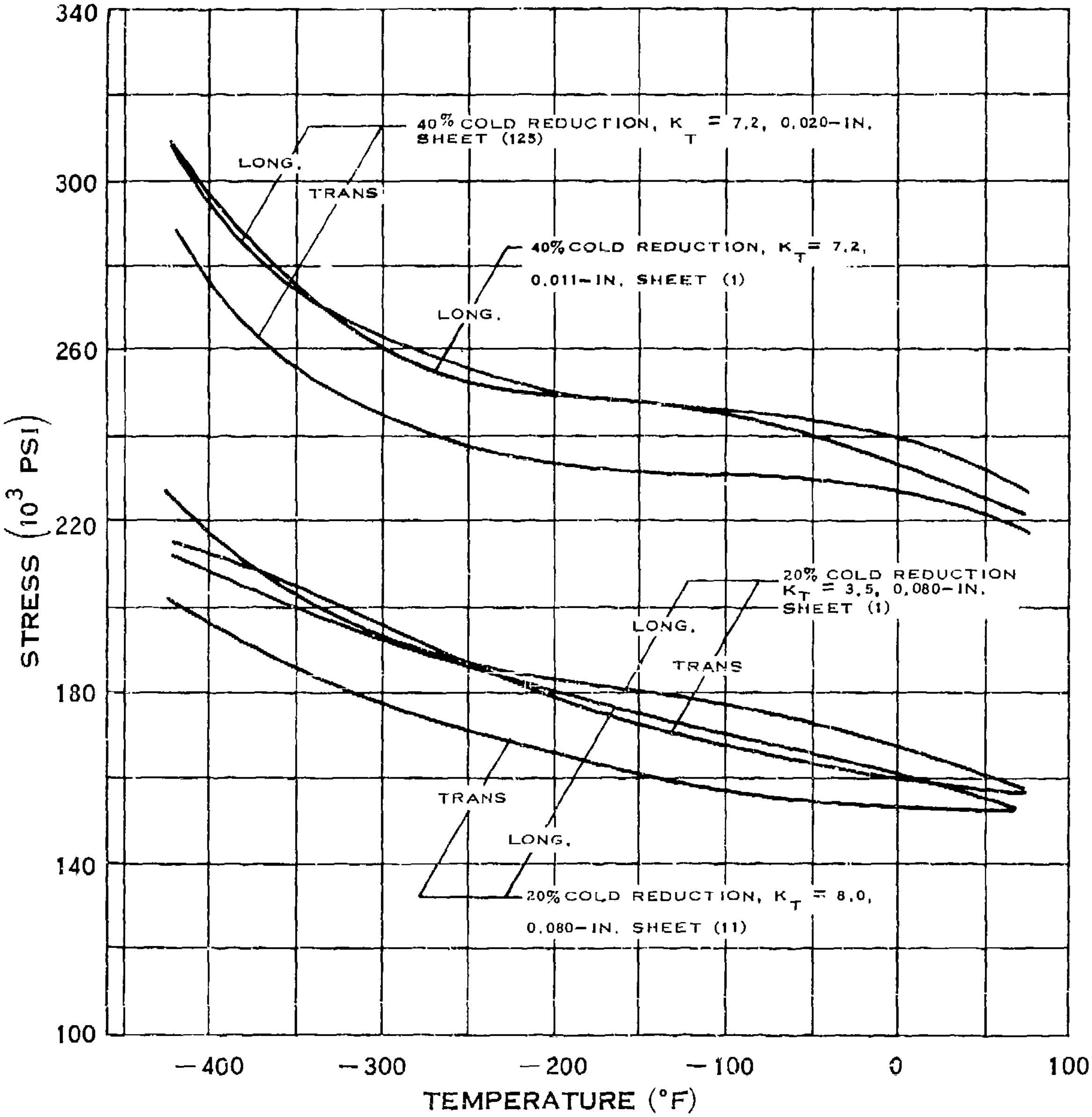
D.6.c



ELONGATION OF HASTELLOY B

(7-65)

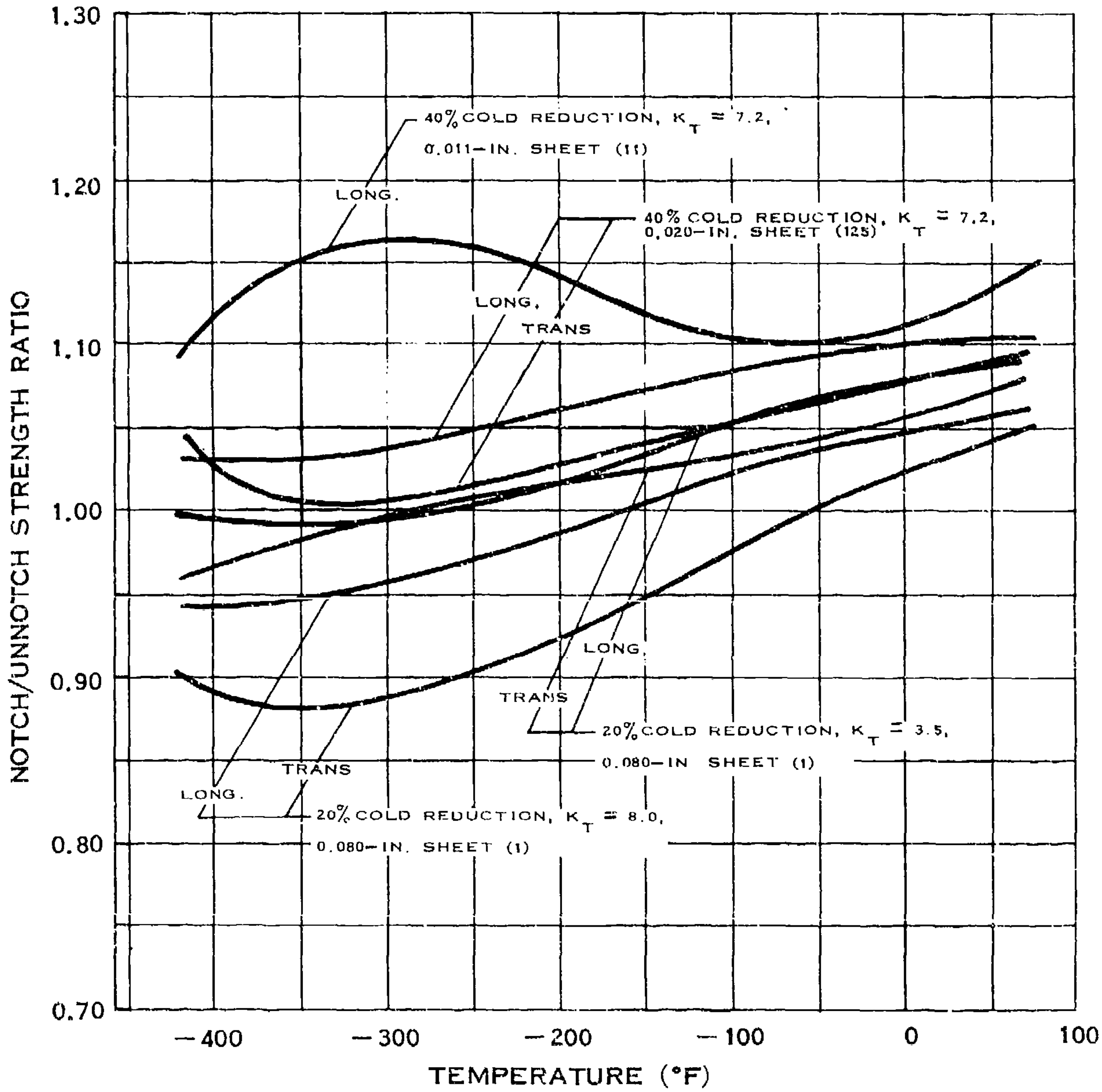
D.6.e



NOTCH TENSILE STRENGTH OF HASTELLOY B

(7-65)

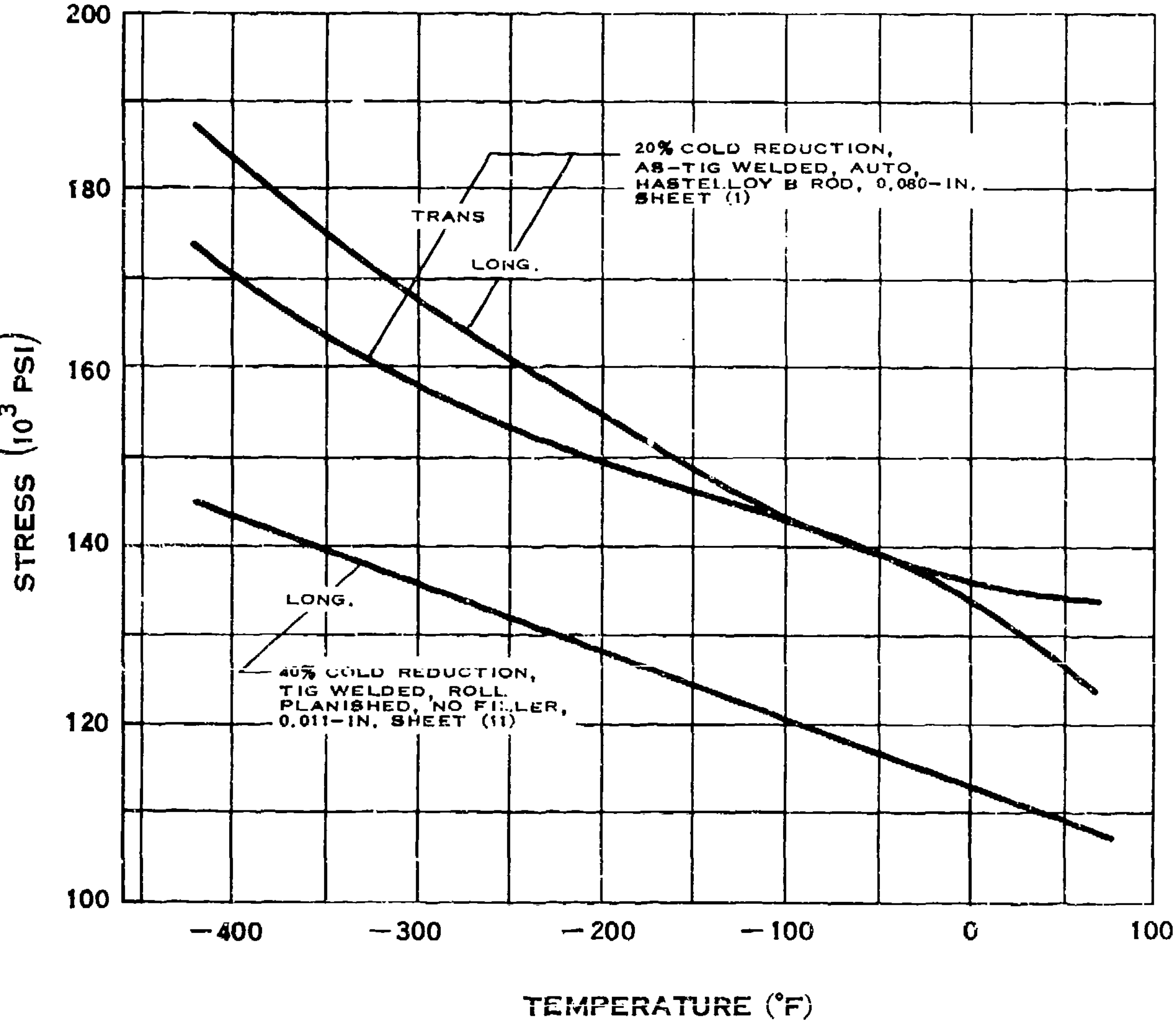
D.6.e-1



NOTCH STRENGTH RATIO OF HASTELLOY B

(7-65)

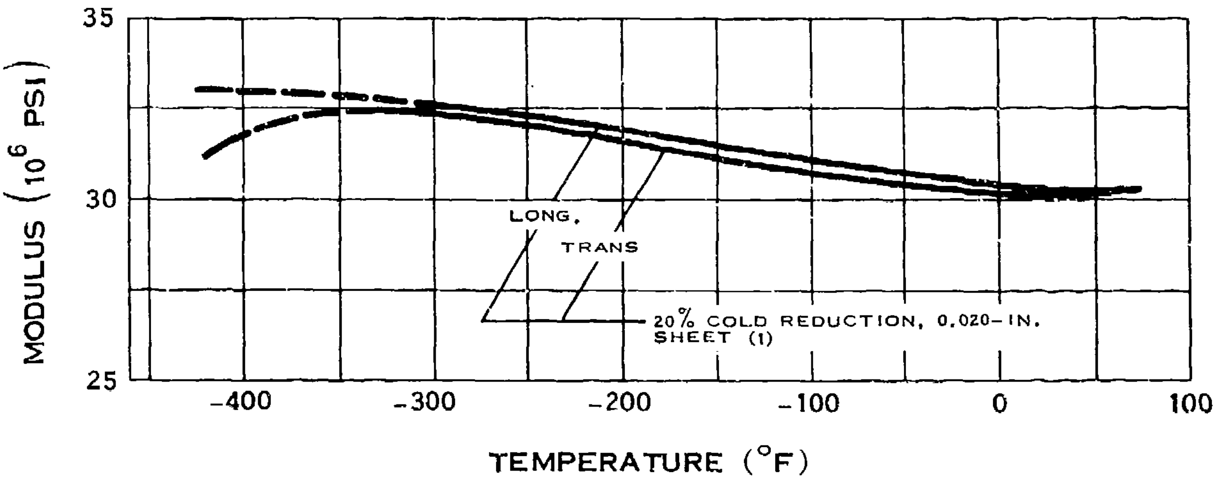
D.6.g



WELD TENSILE STRENGTH OF HASTELLOY B

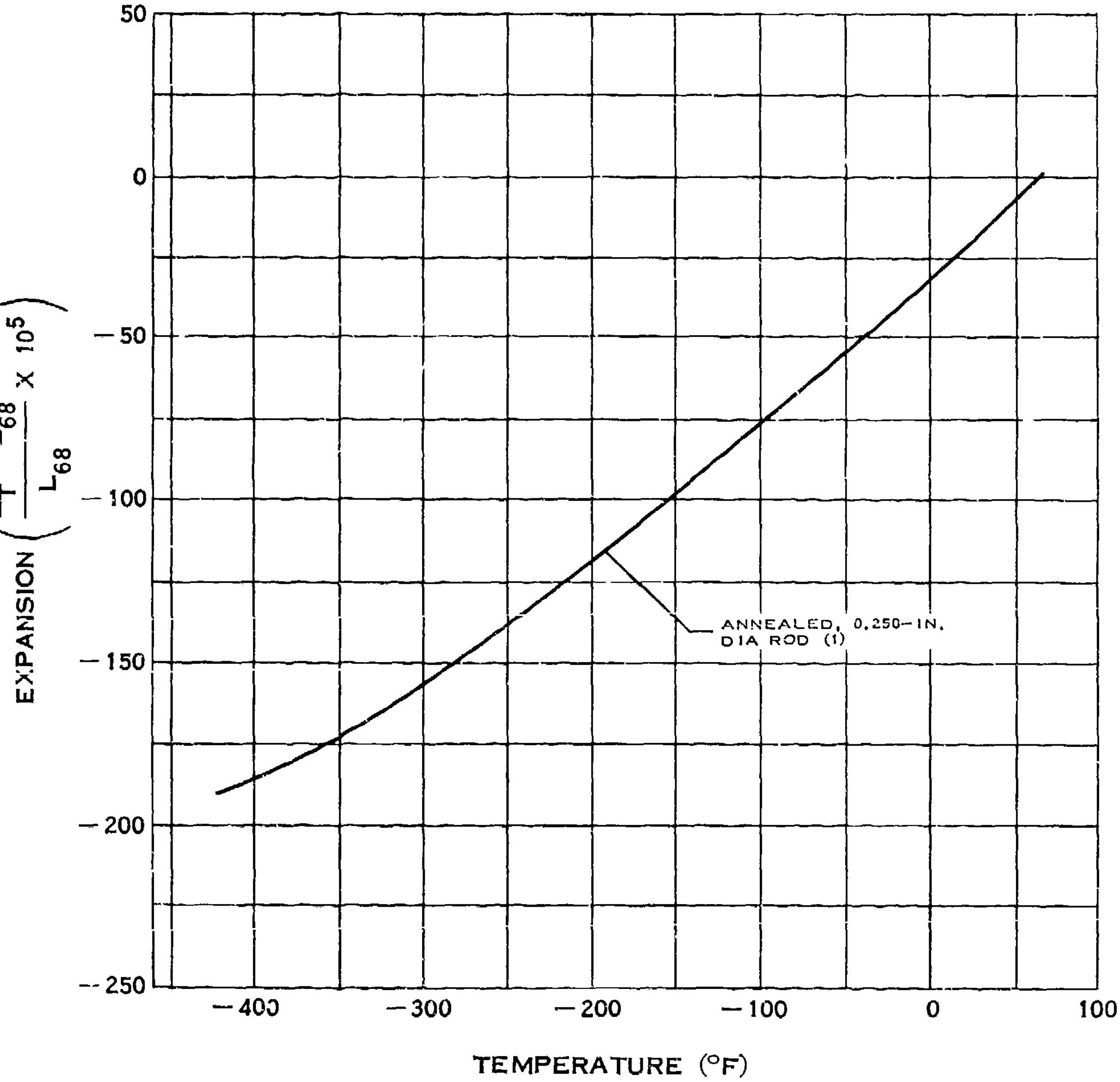
(7−64)

D.6.i



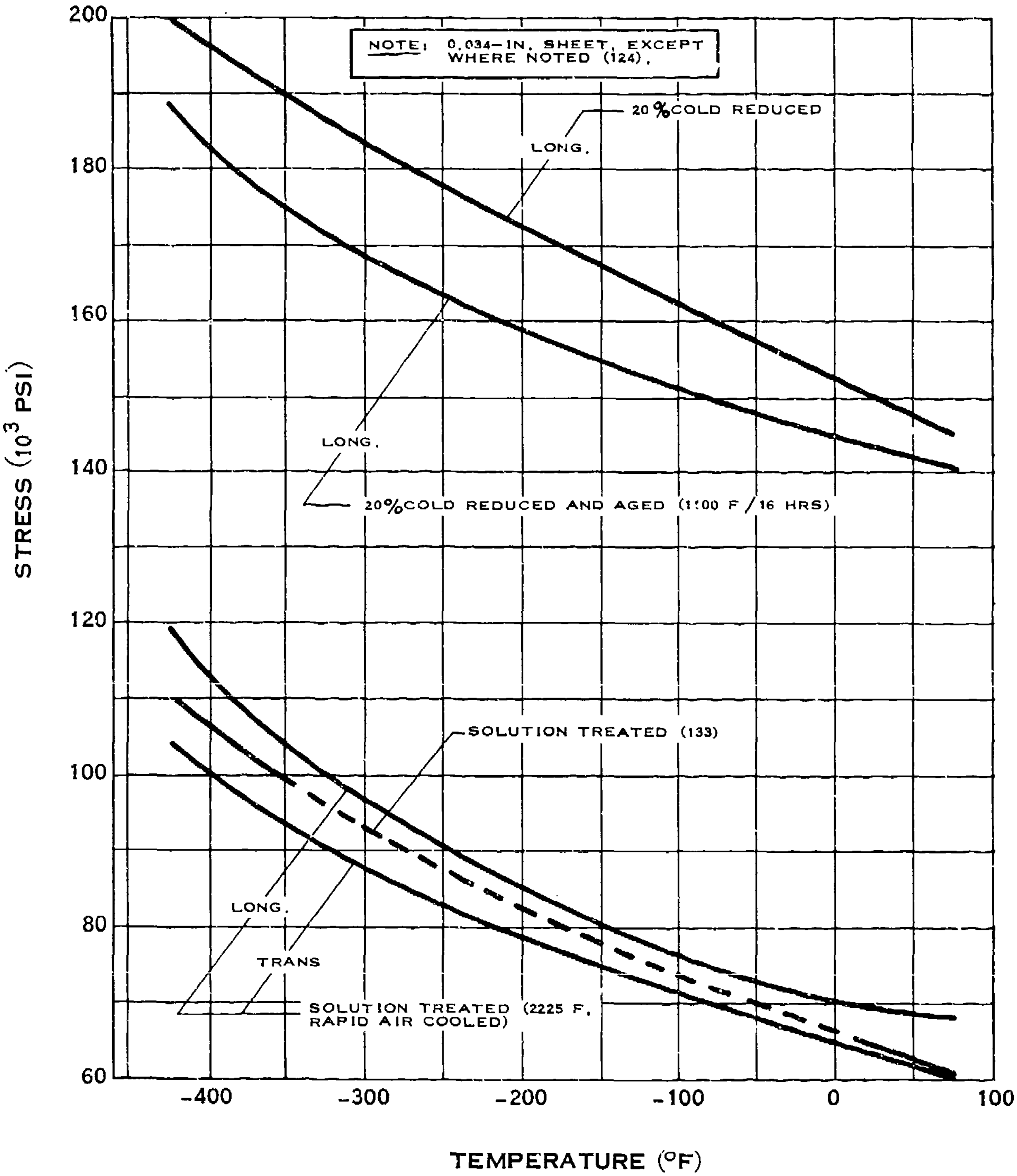
MODULUS OF ELASTICITY OF HASTELLOY B

D.6.t



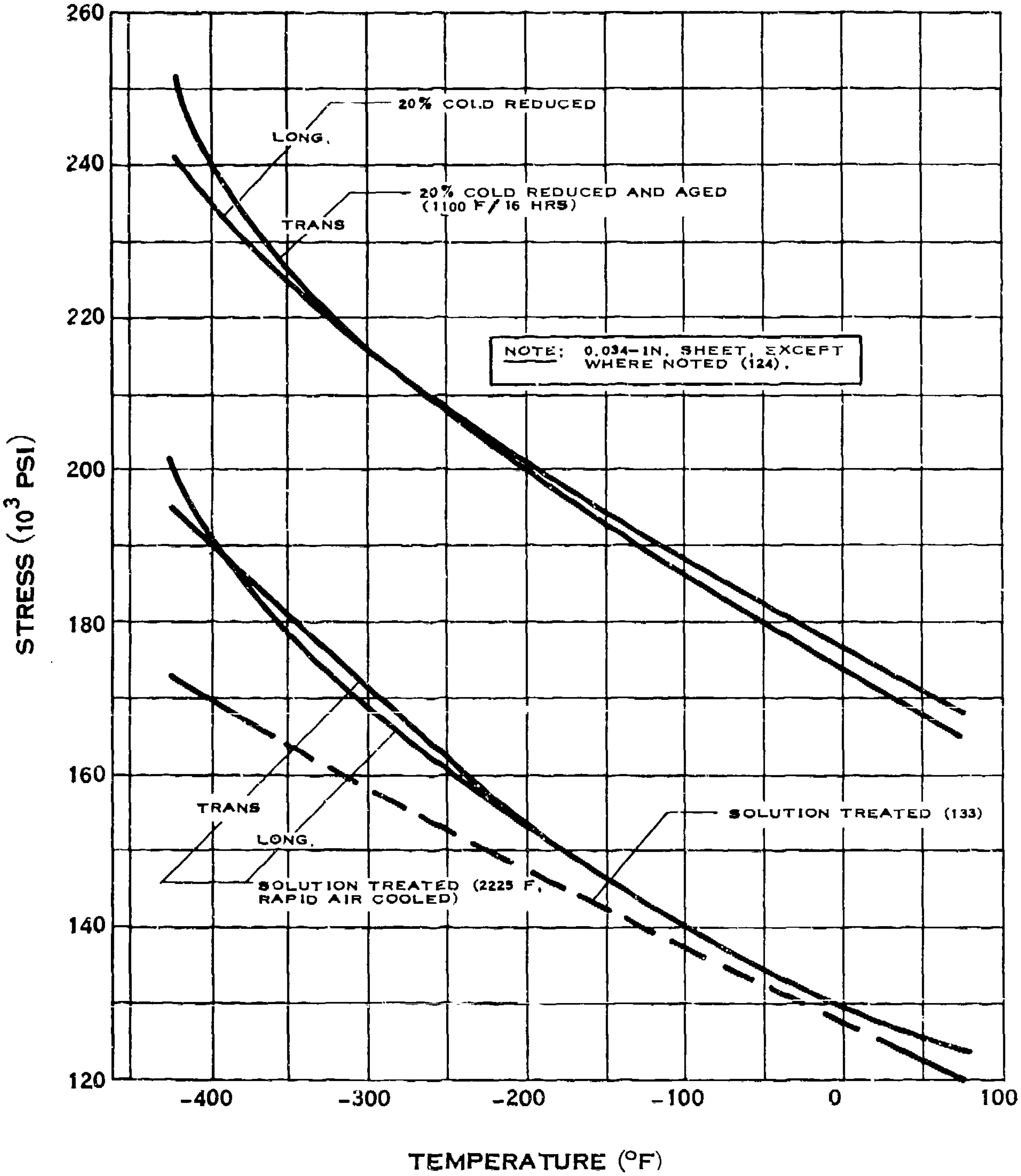
THERMAL EXPANSION OF HASTELLOY B

D.7.a



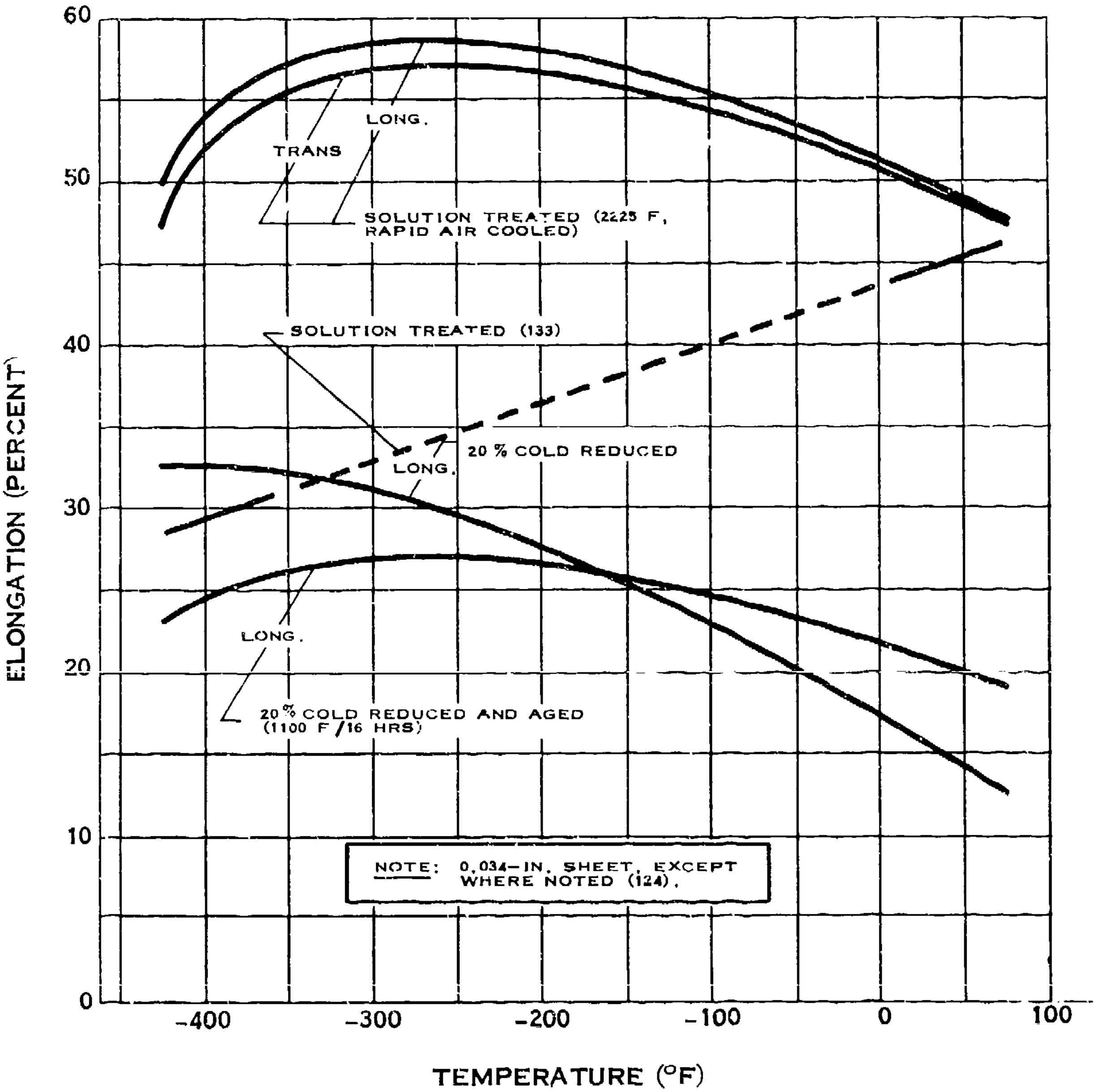
YIELD STRENGTH OF HASTELLOY C

(7-65)



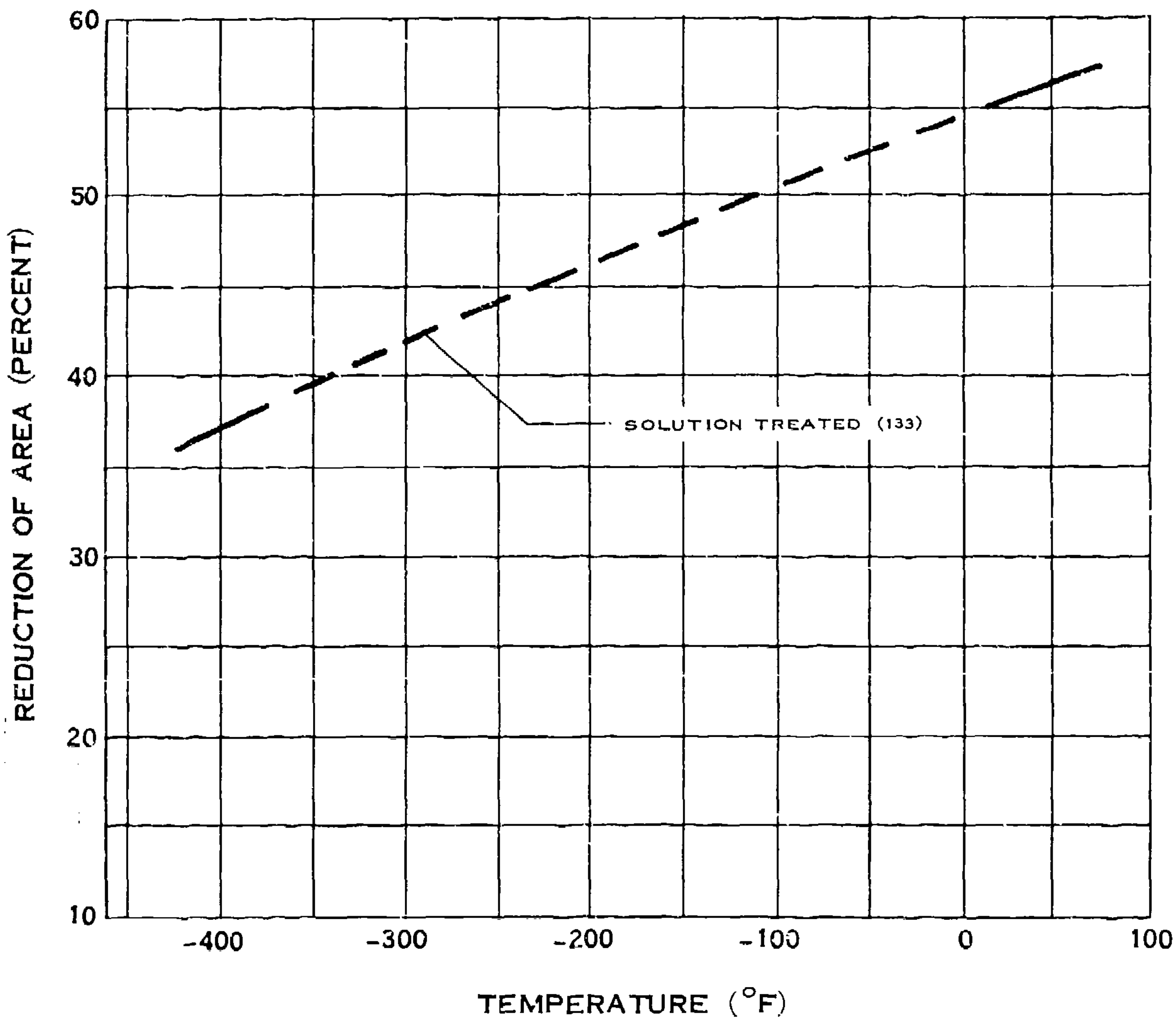
TENSILE STRENGTH OF HASTELLOY C

D.7.c

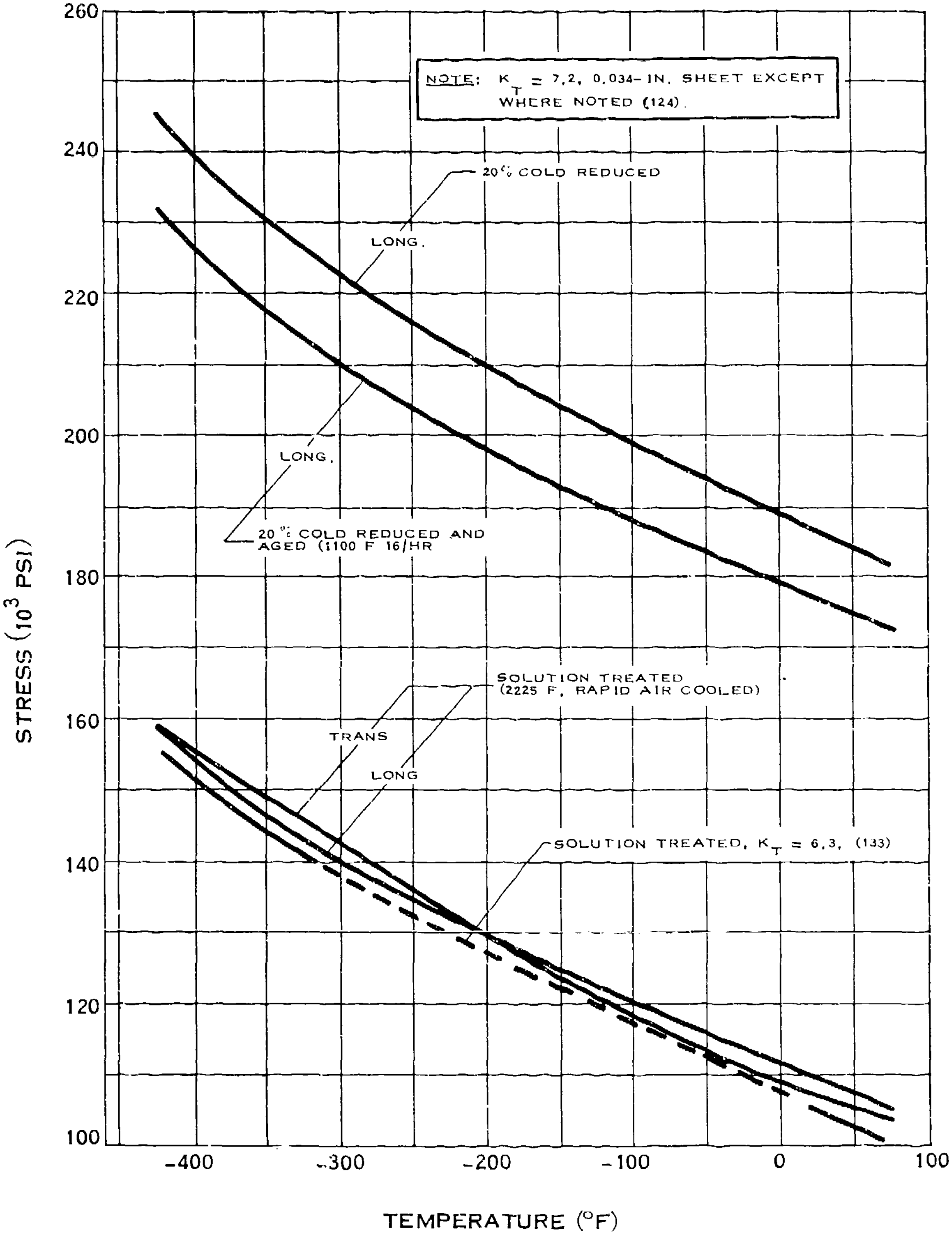


ELONGATION OF HASTELLOY C

D.7.d



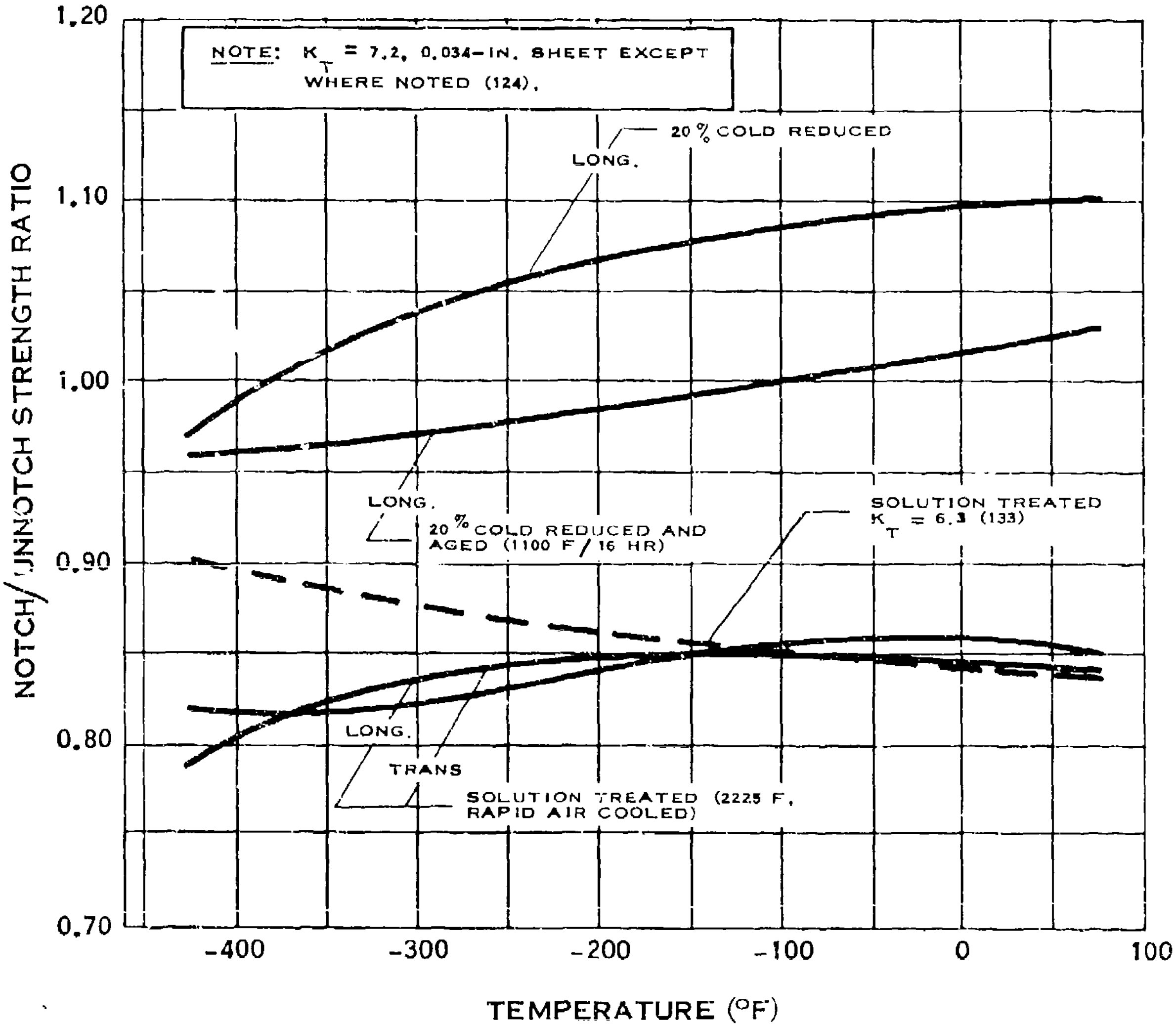
REDUCTION OF AREA OF HASTELLOY C



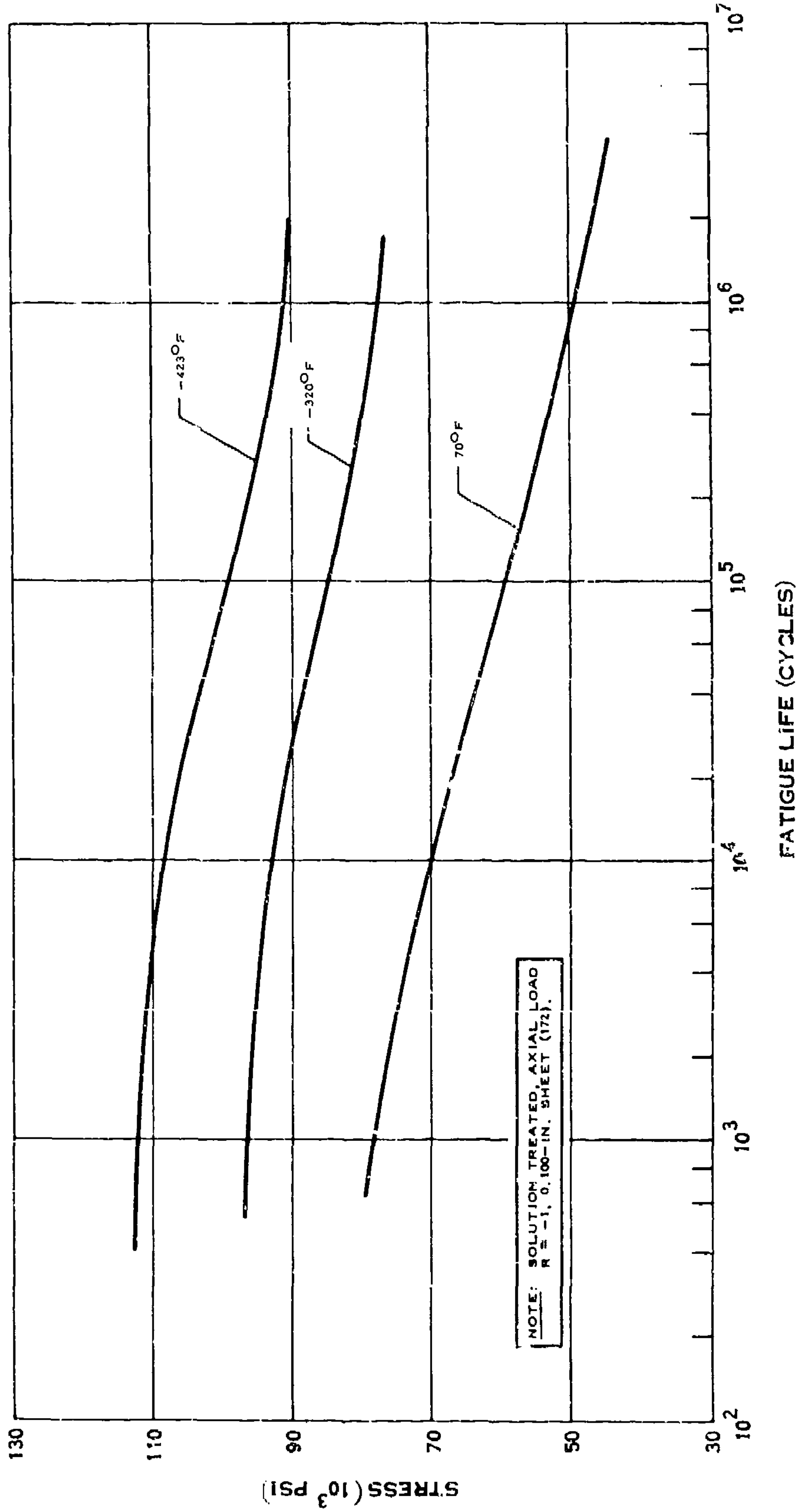
NOTCH TENSILE STRENGTH OF HASTELLOY C

(7-65)

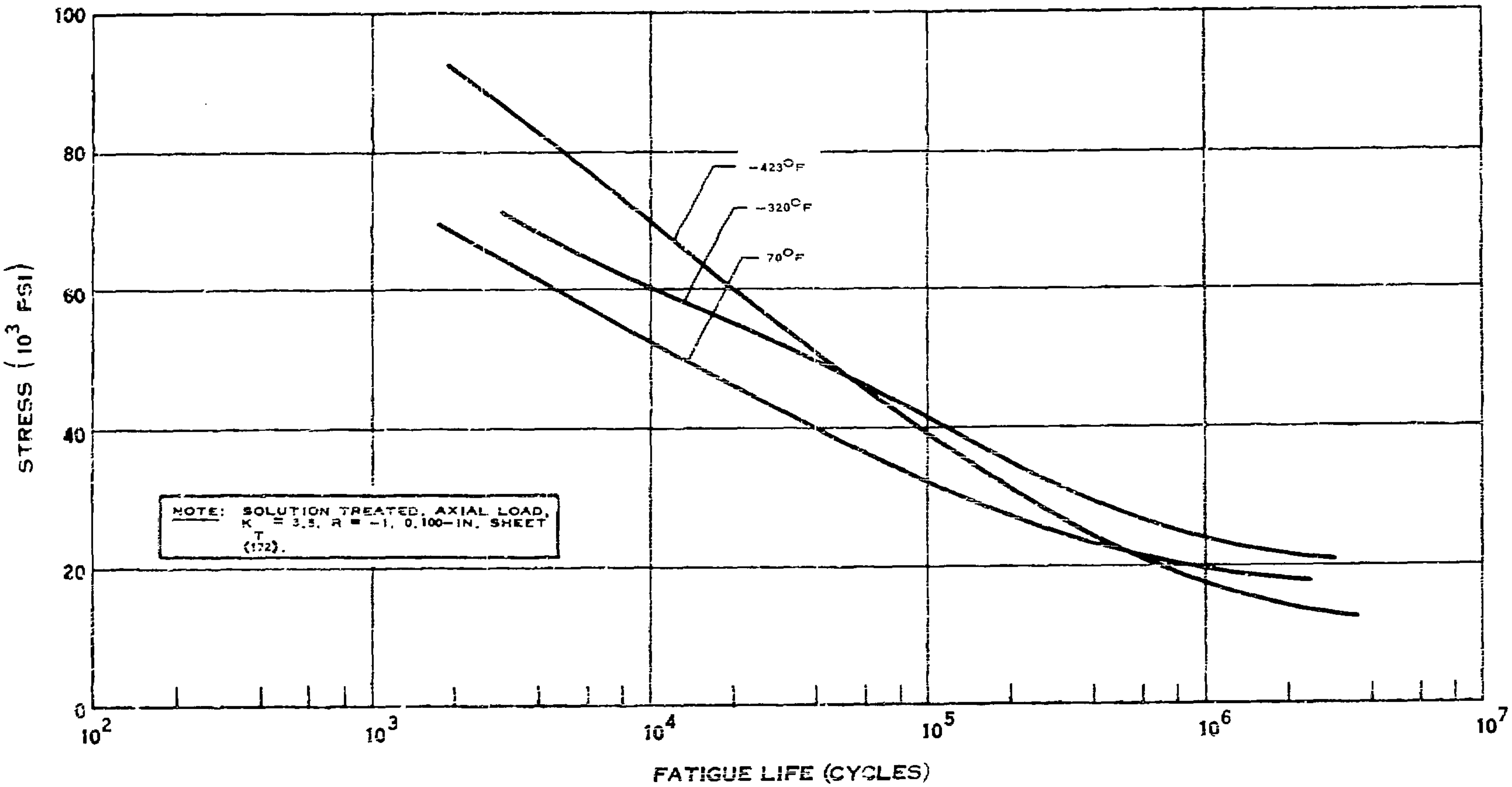
D.7.e-1



NOTCH STRENGTH RATIO OF HASTELLOY C

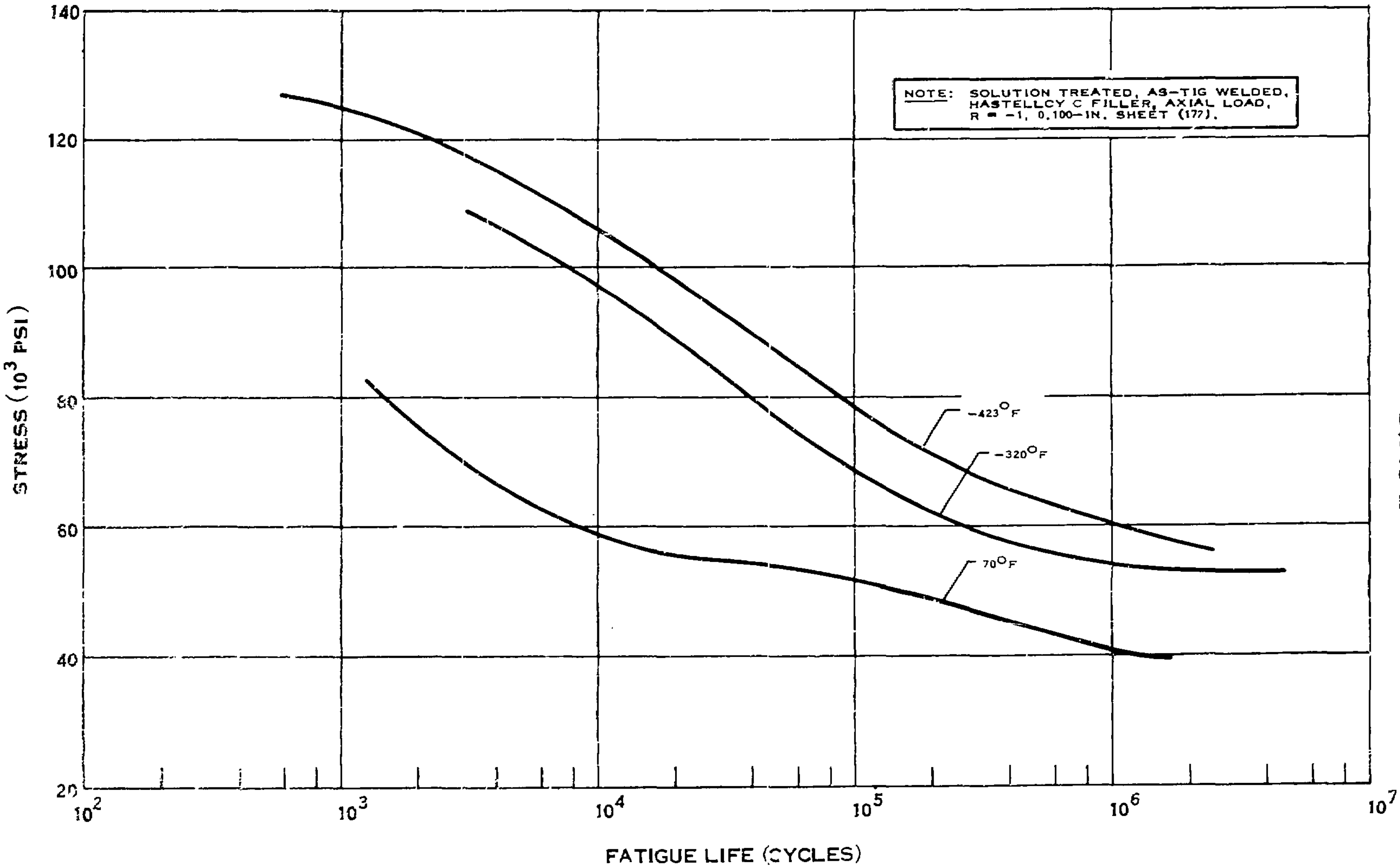


FATIGUE STRENGTH OF HASTELLOY C



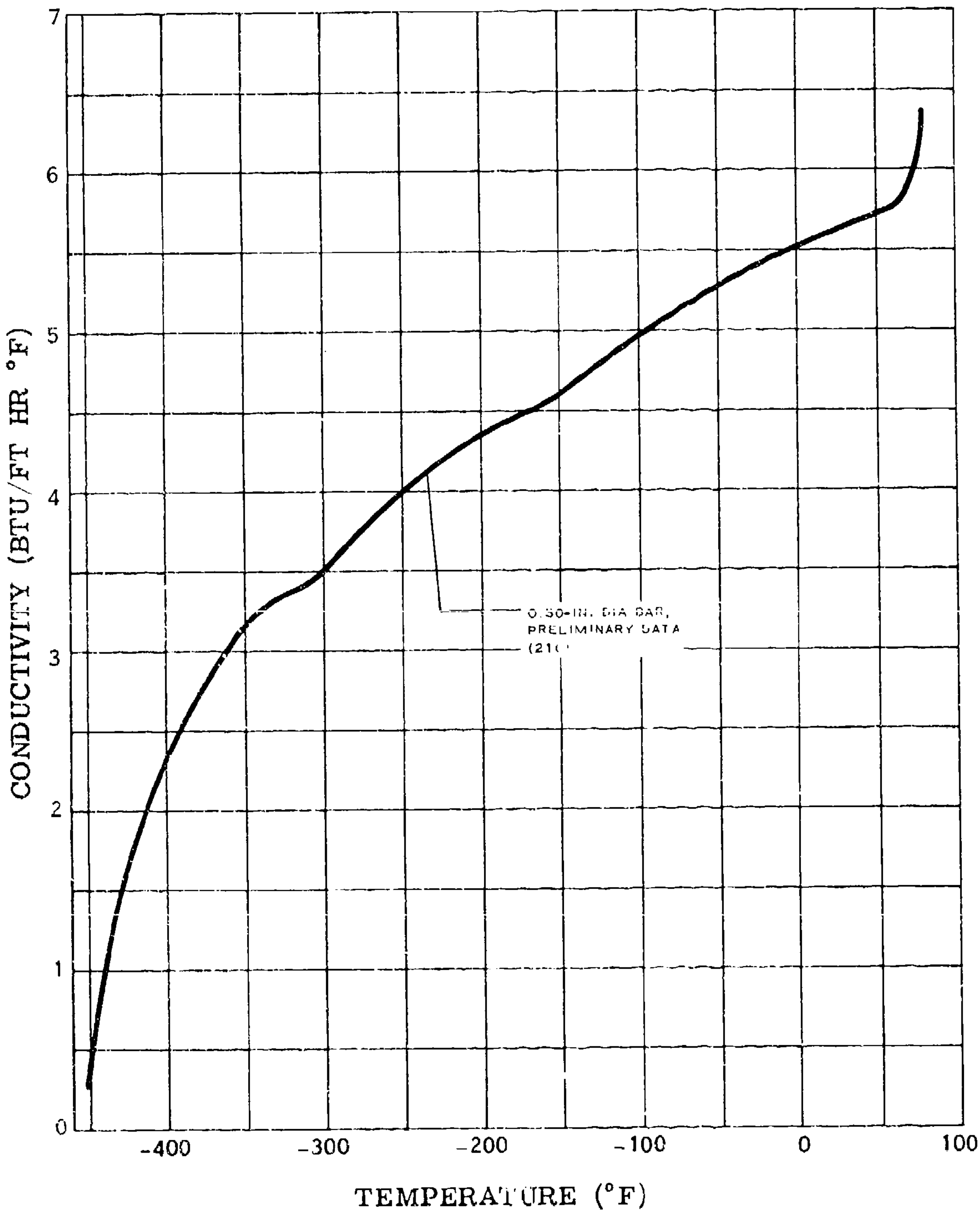
NOTCH FATIGUE STRENGTH OF HASTELLOY C

(3-68)



WELD FATIGUE STRENGTH OF HASTELLOY C

(3-66)



THERMAL CONDUCTIVITY OF HASTELLOY X

(6-68)

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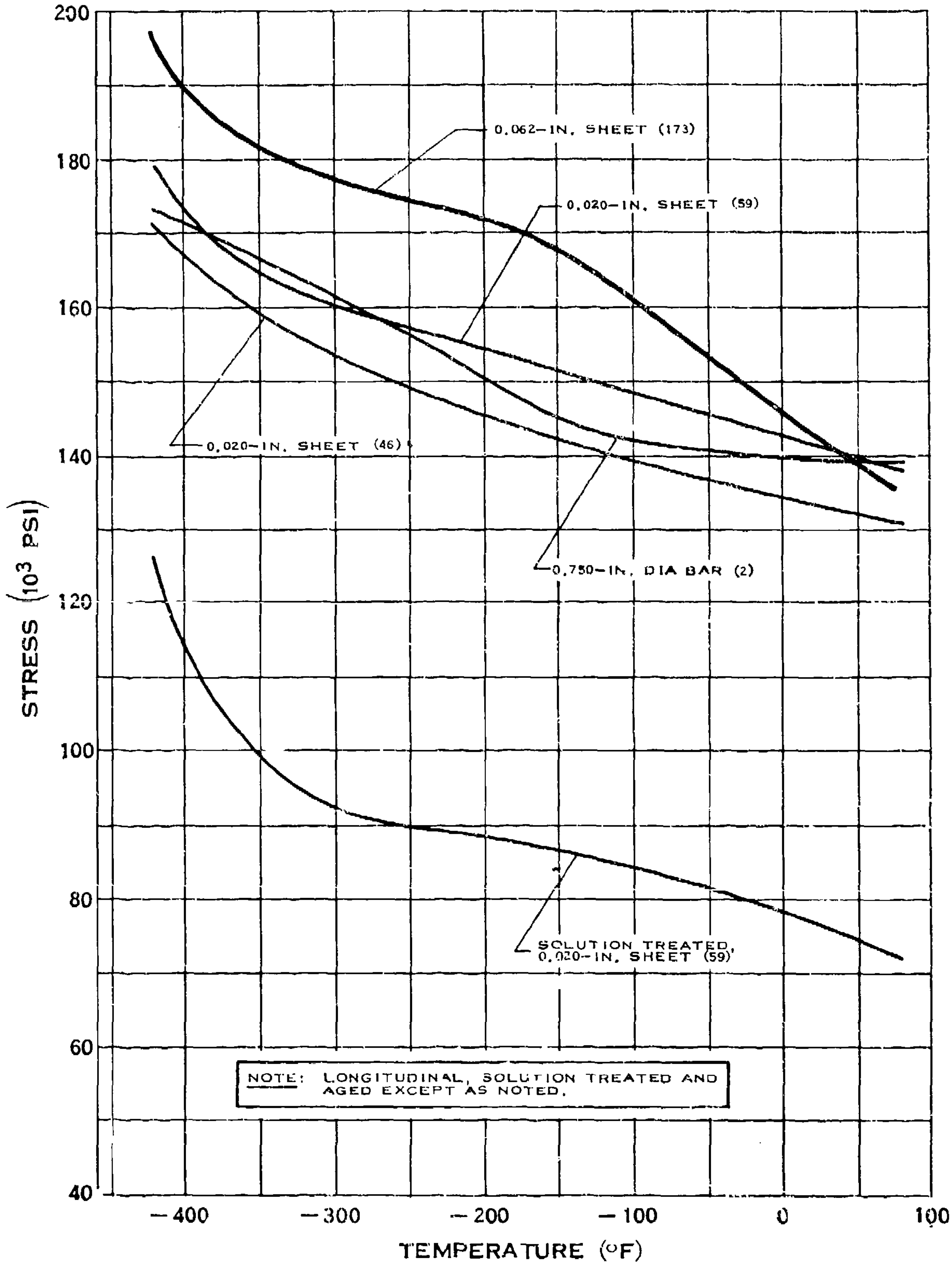

YIELD STRENGTH OF RENE' 41

(3-66)

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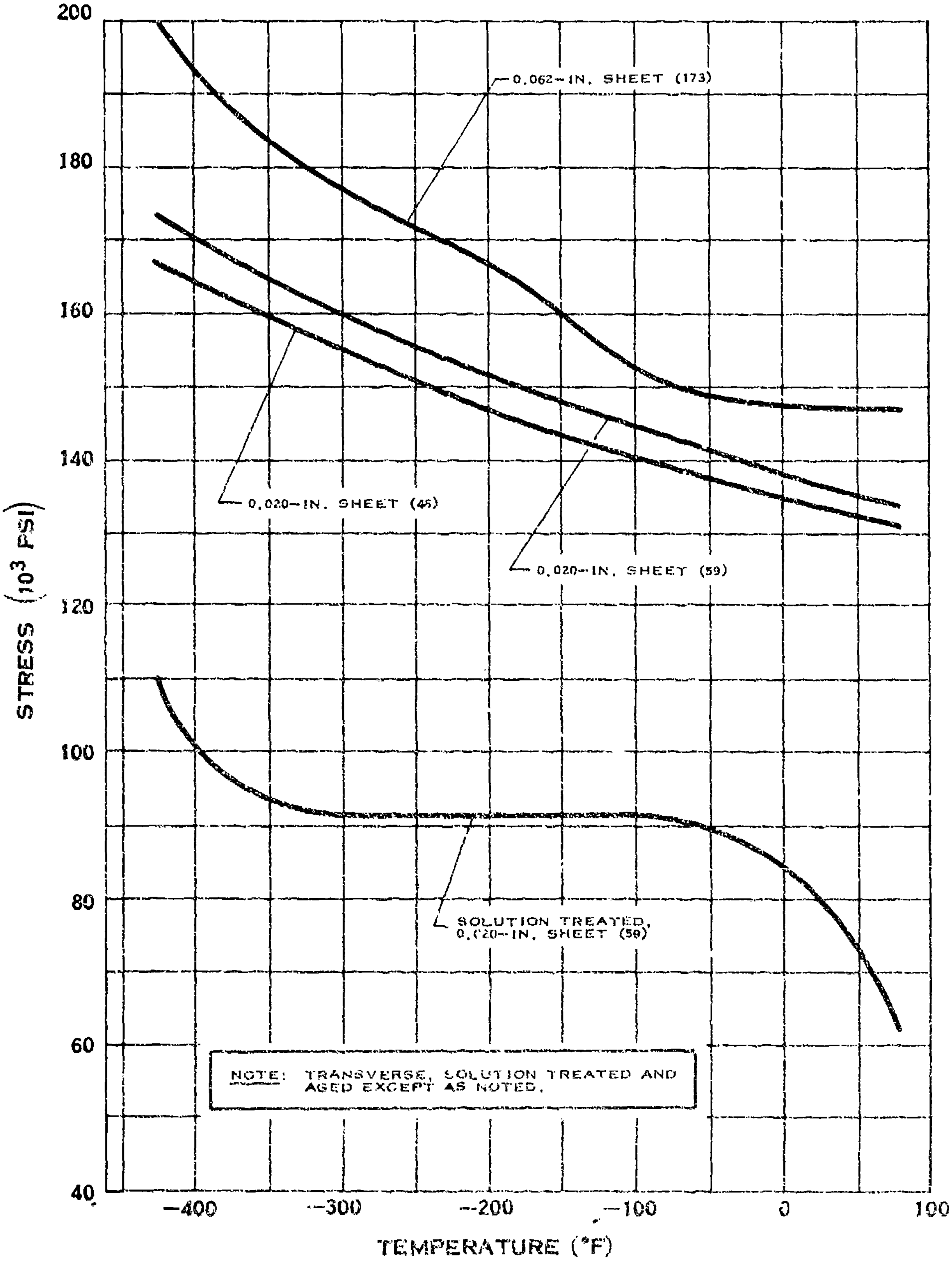
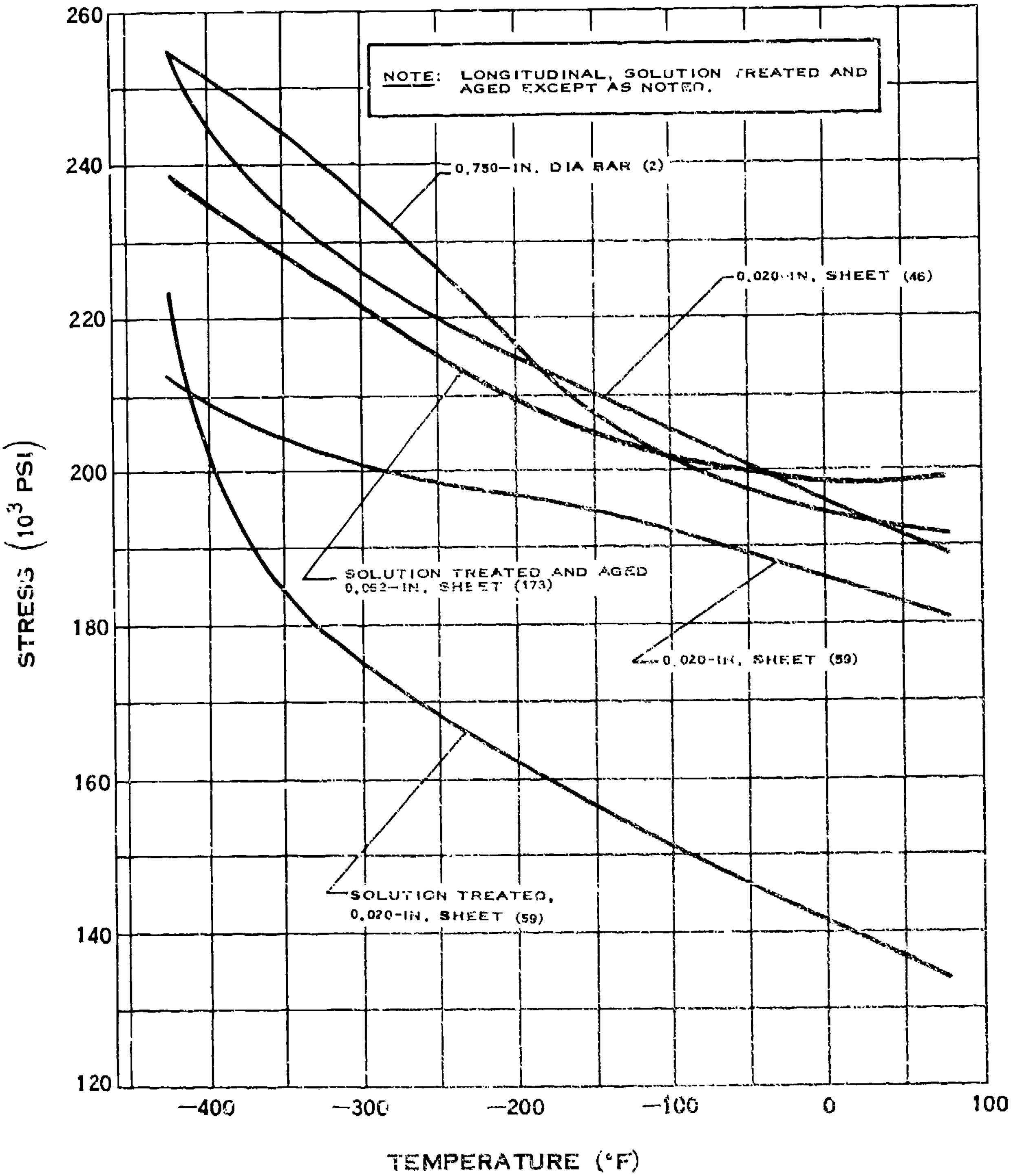
D.9.a-1



(3-66)

YIELD STRENGTH OF RENE' 41

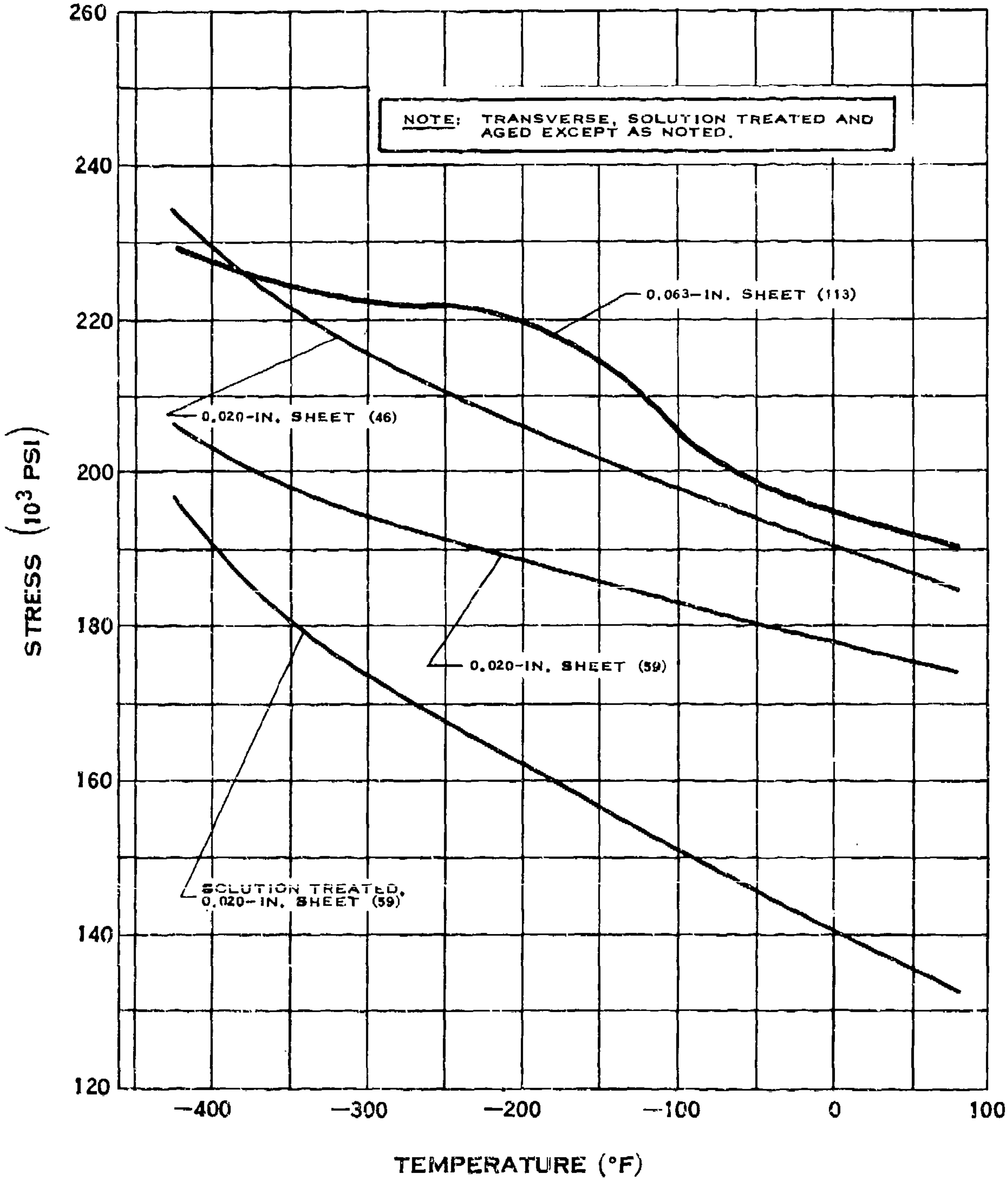
D.9.b



TENSILE STRENGTH OF RENE' 41

(3-66)

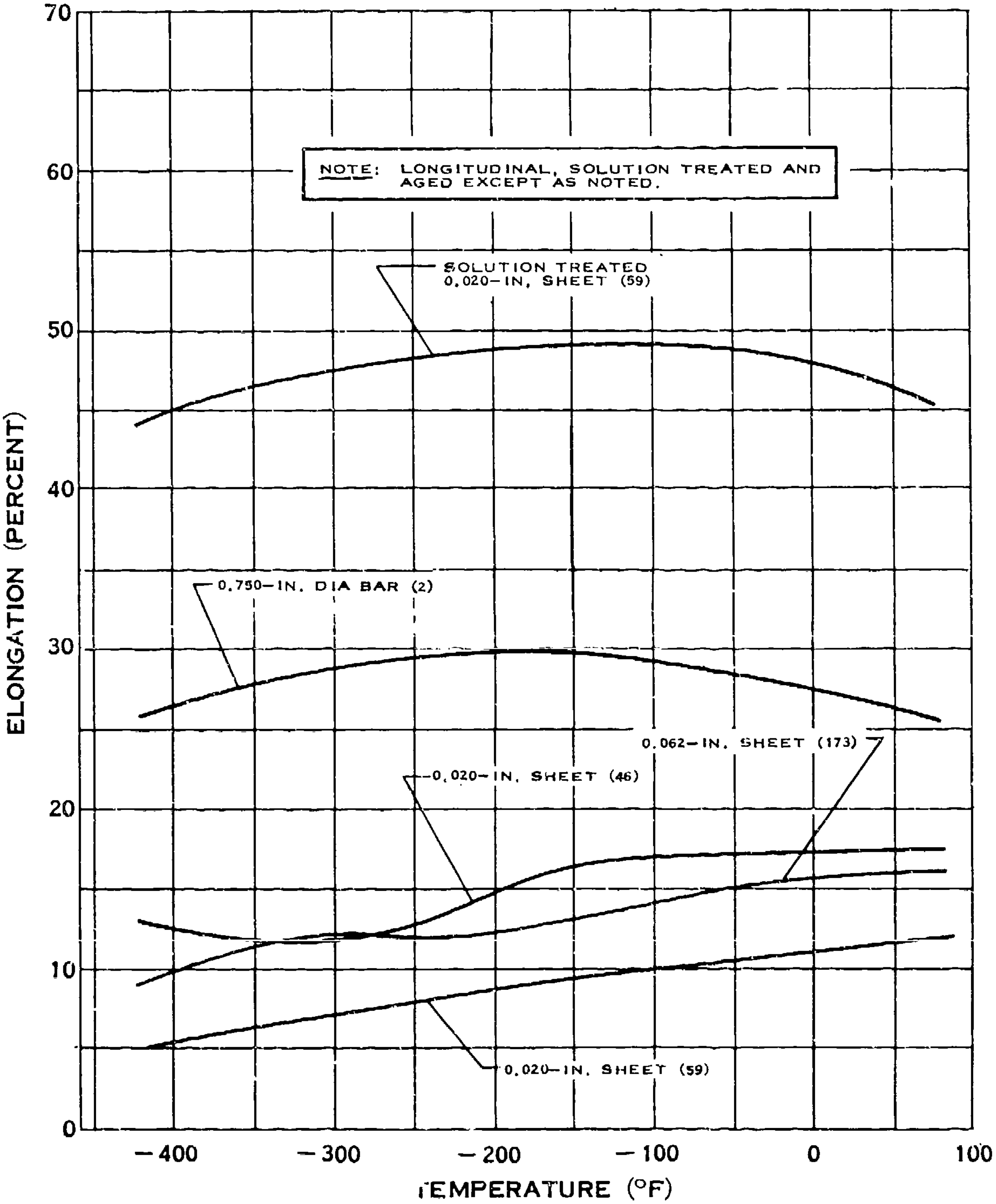
D.9.b-1



TENSILE STRENGTH OF RENE' 41

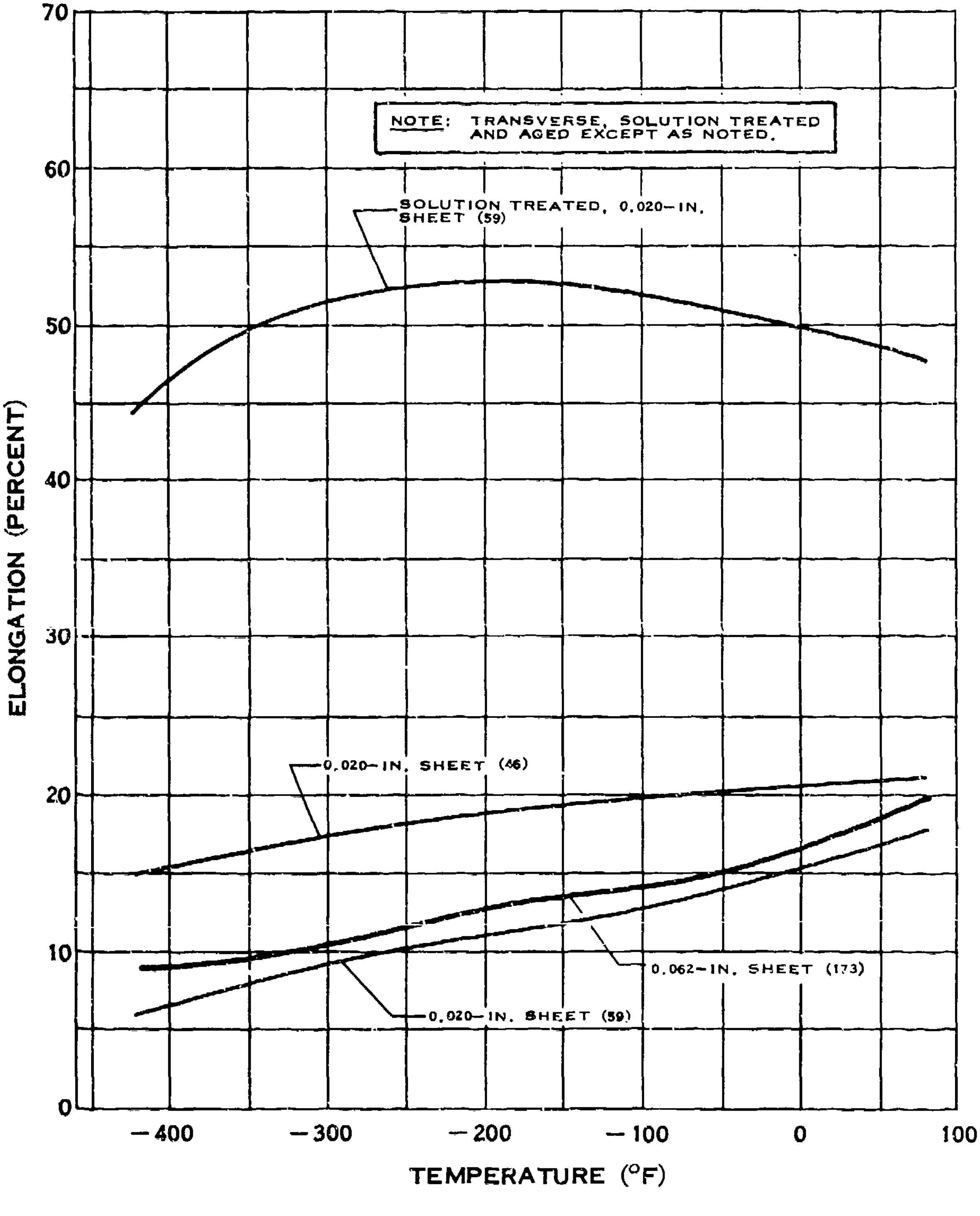
(3-66)

D.9.c



ELONGATION OF RENE' 41

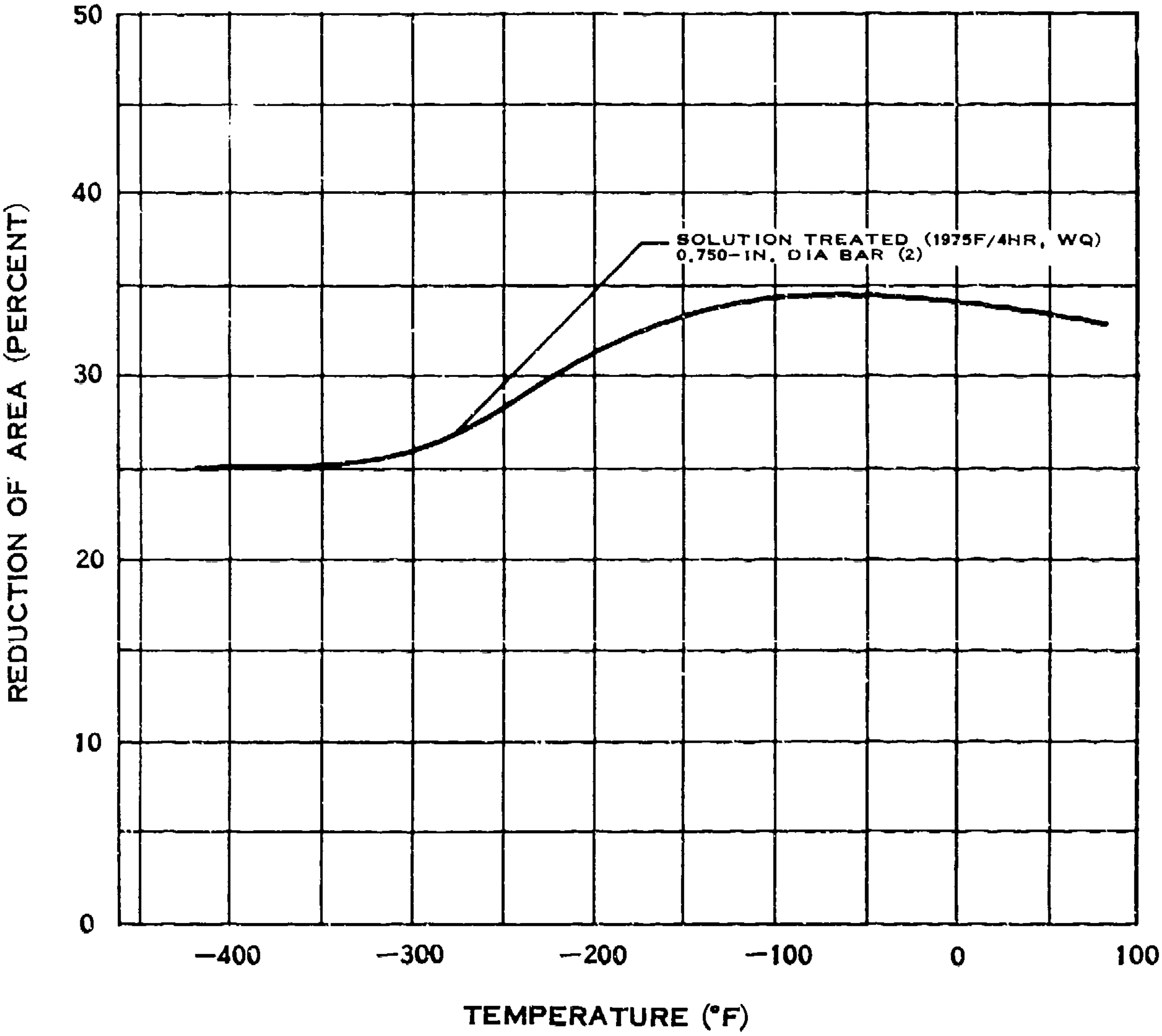
D.9.c-1



ELONGATION OF RENE' 41

(3-64)

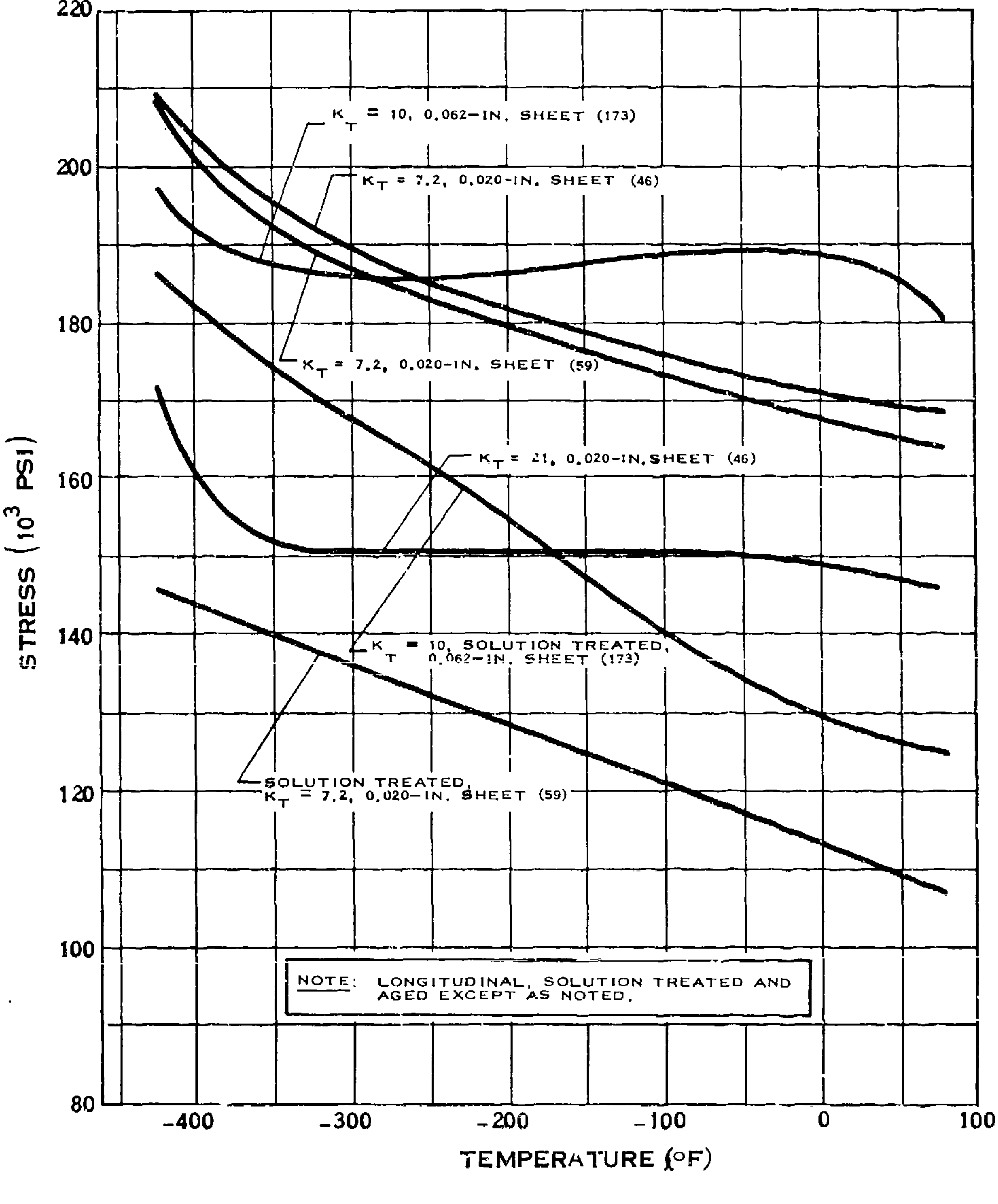
D.9.d



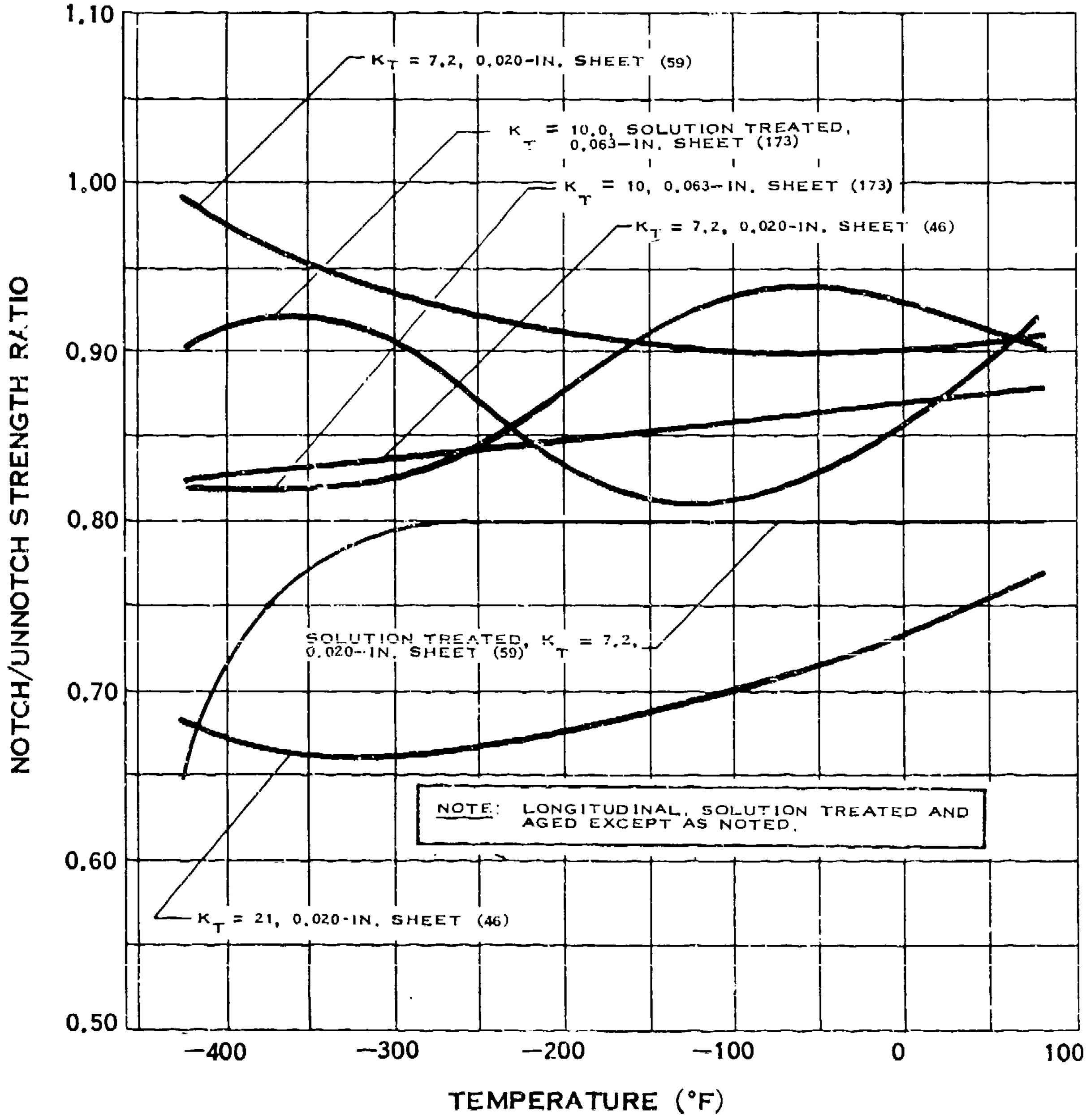
REDUCTION OF AREA OF RENE' 41

(7−64)

D.9.e

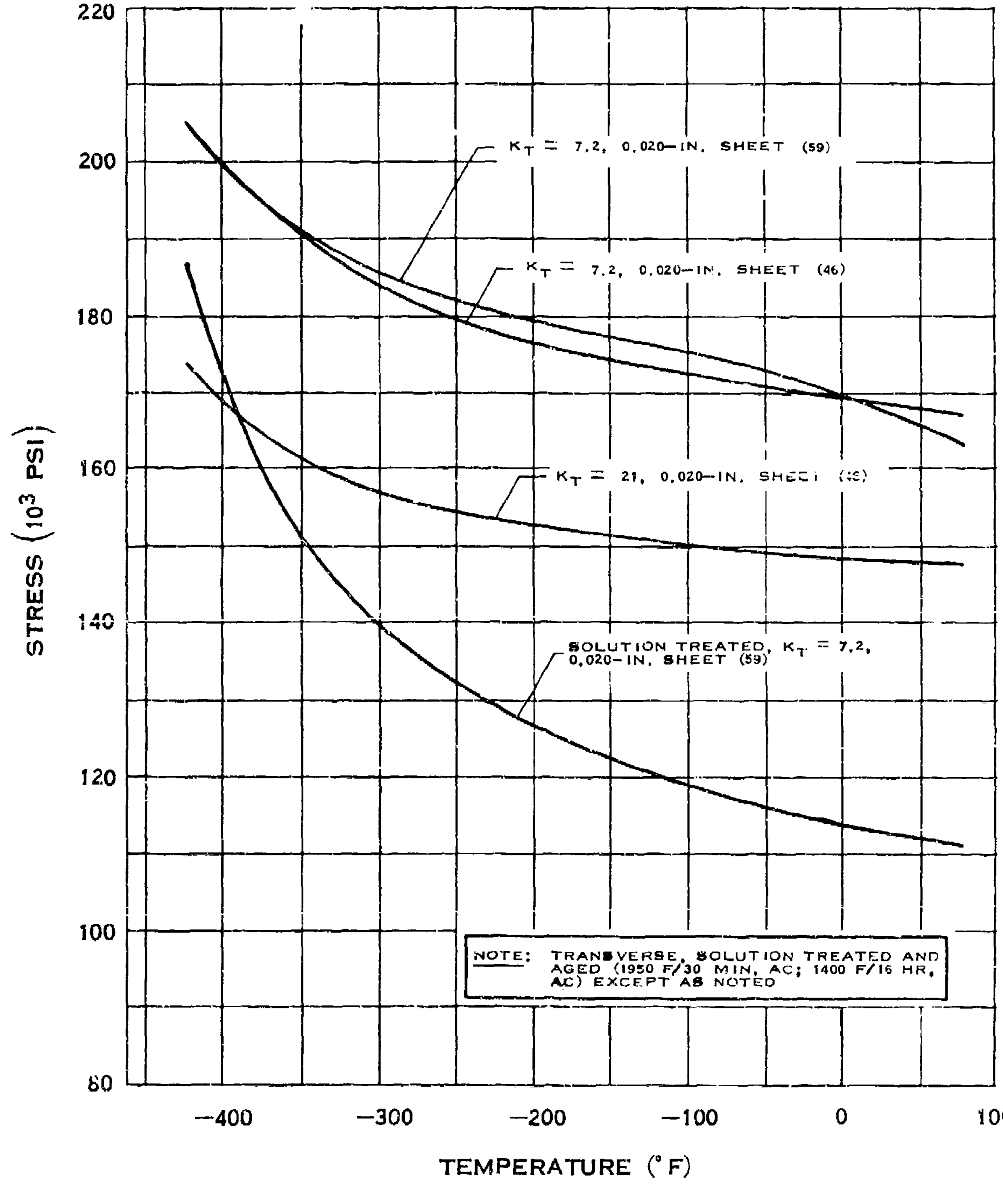


NOTCH TENSILE STRENGTH OF RENE' 41



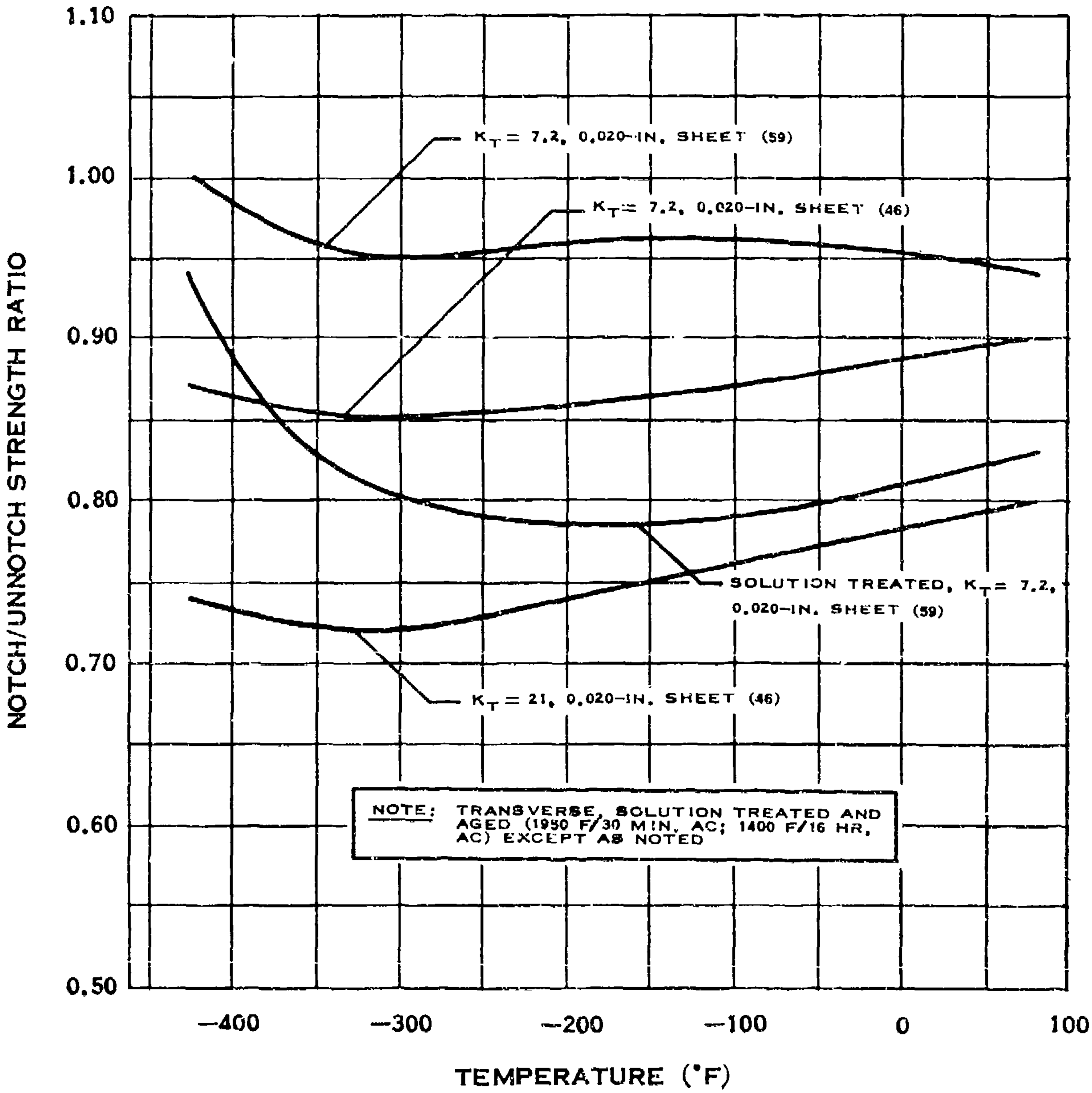
NOTCH STRENGTH RATIO OF RENE' 41

(3–66)



NOTCH TENSILE STRENGTH OF RENE' 41

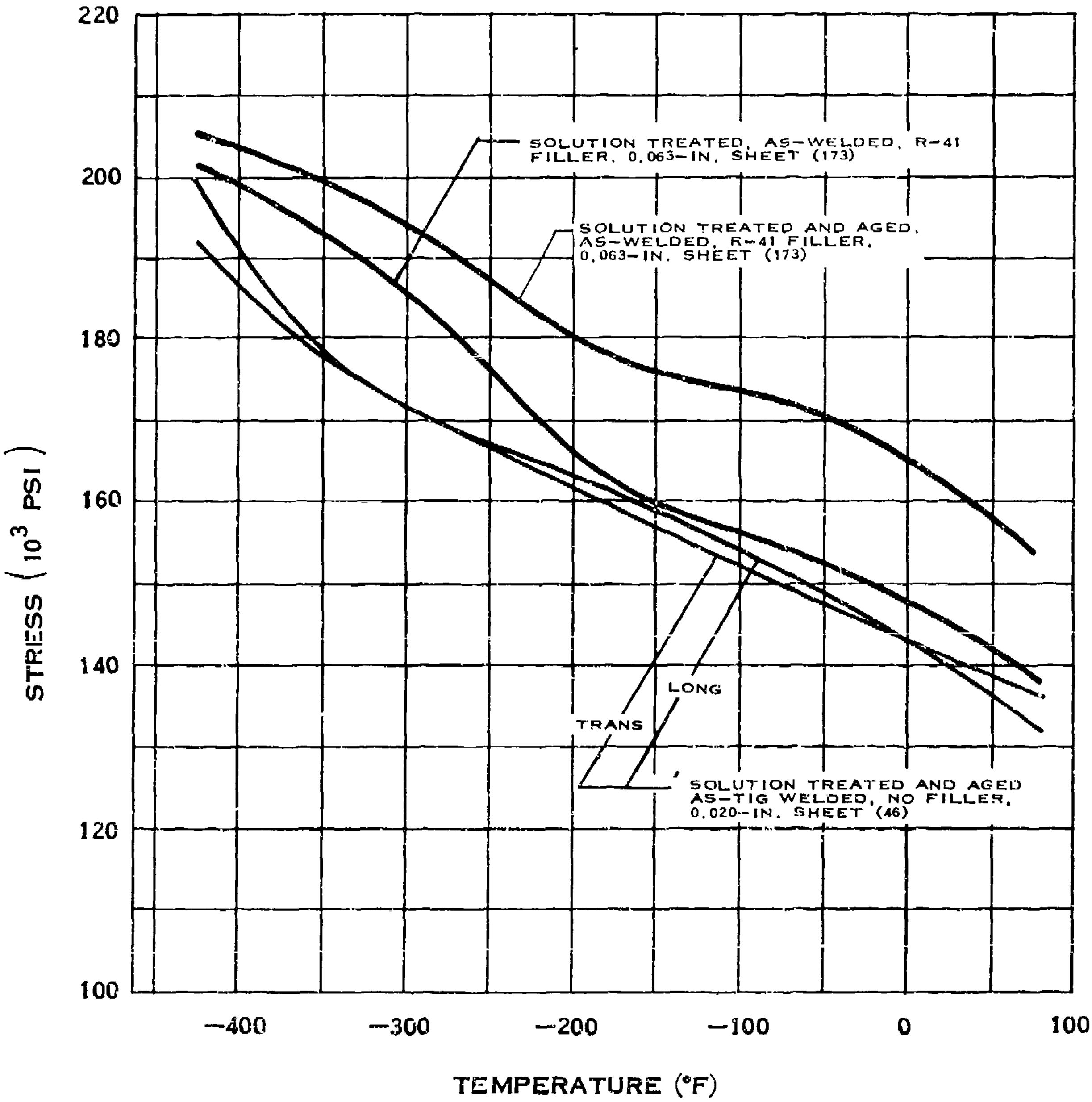
D.9.e-3



NOTCH STRENGTH RATIO OF RENE' 41

(7-64)

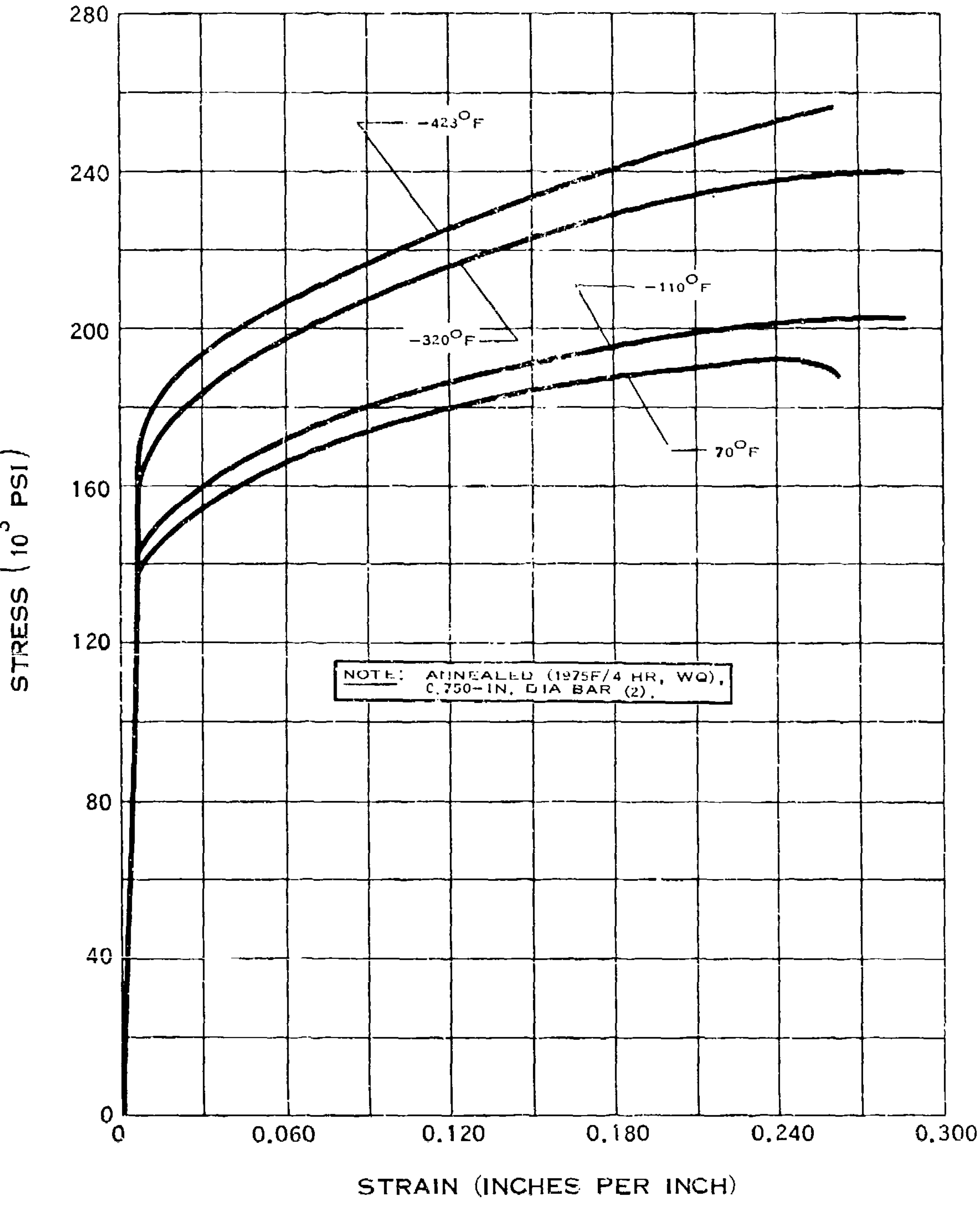
D.9.g



WELD TENSILE STRENGTH OF RENE' 41

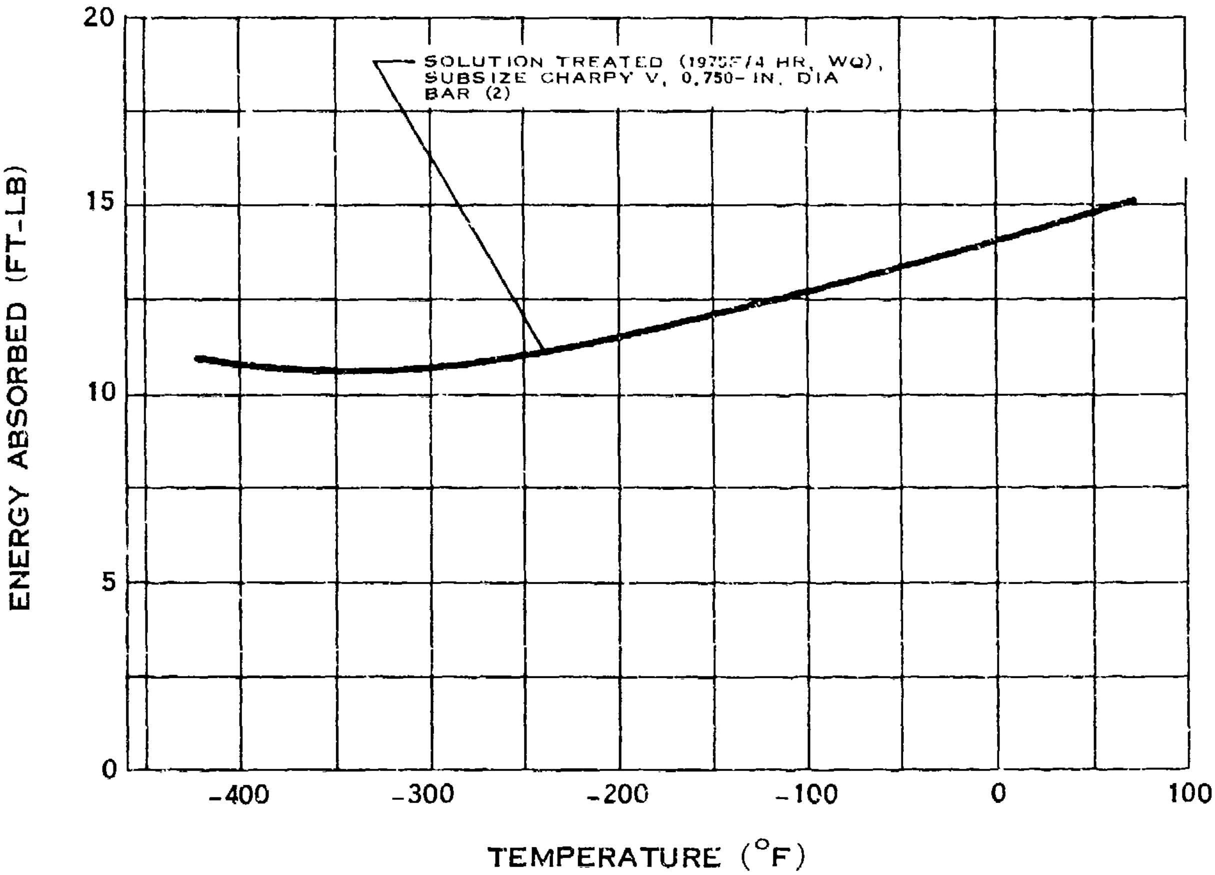
(3-66)

D.9.h



STRESS-STRAIN DIAGRAM FOR RENE' 41

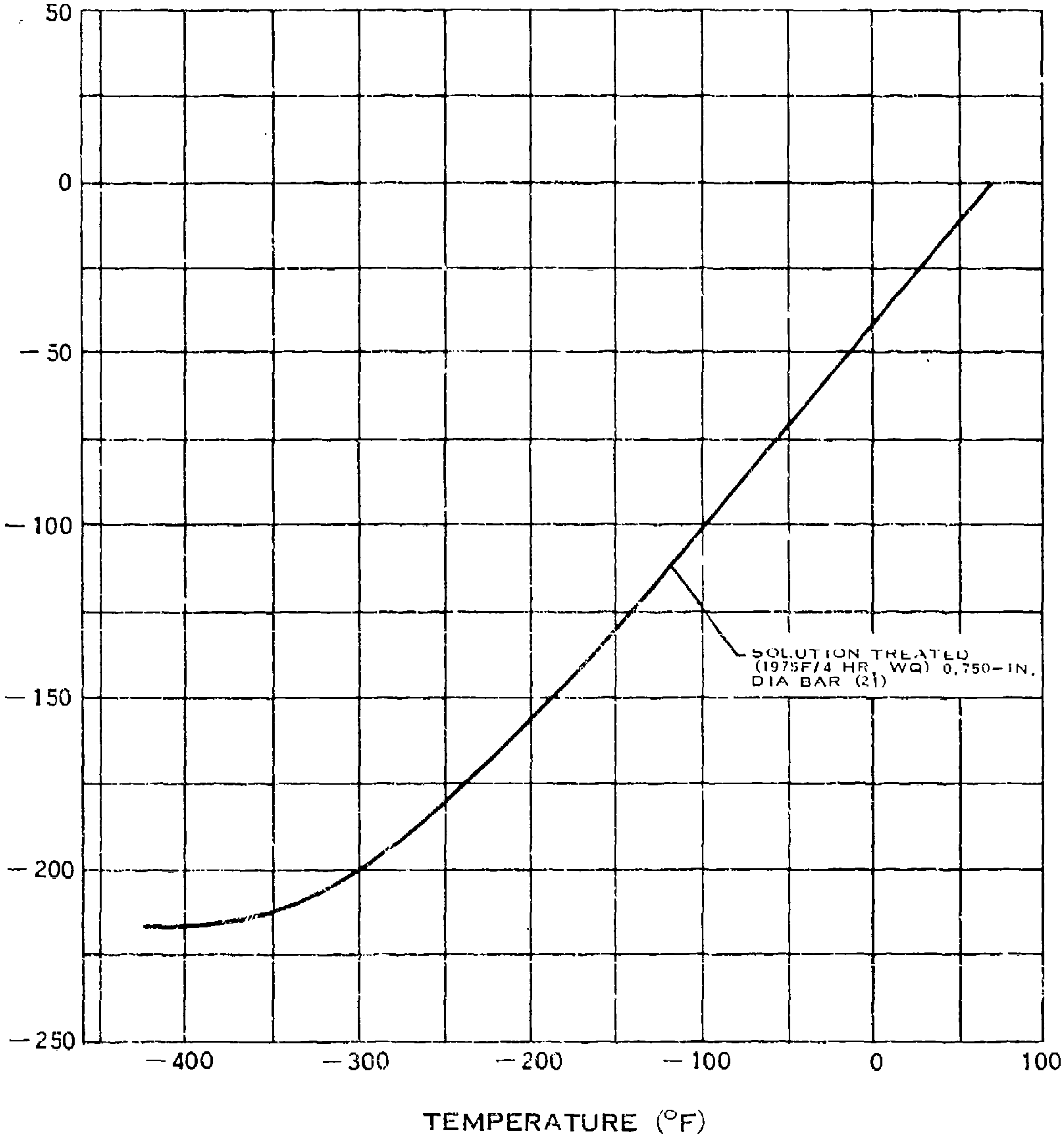
D.9.j



IMPACT STRENGTH OF RENE' 41

(7-64)

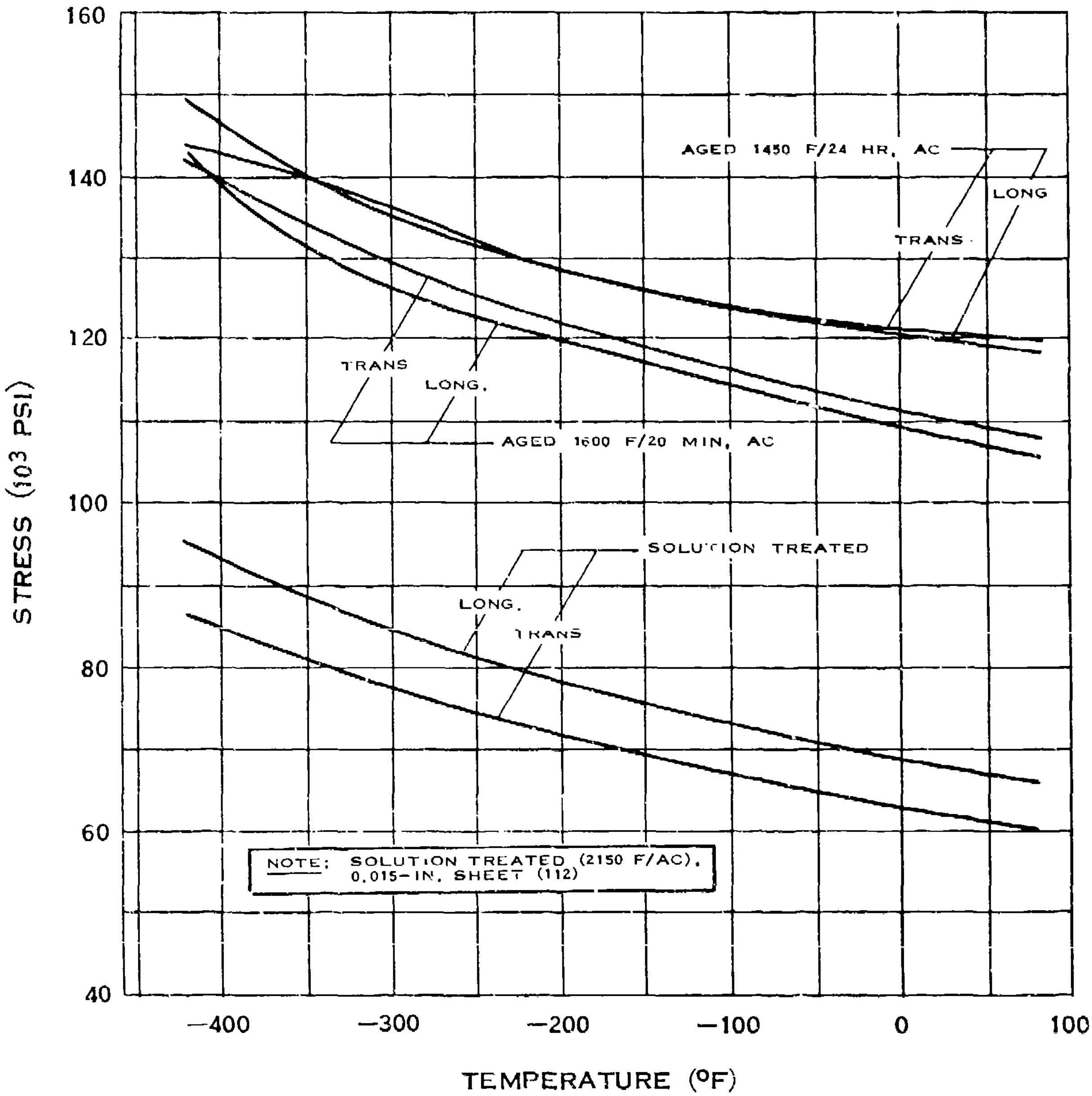
D.9.t



THERMAL EXPANSION OF RENÉ 41

(7-64)

D.10.a



YIELD STRENGTH OF R-235

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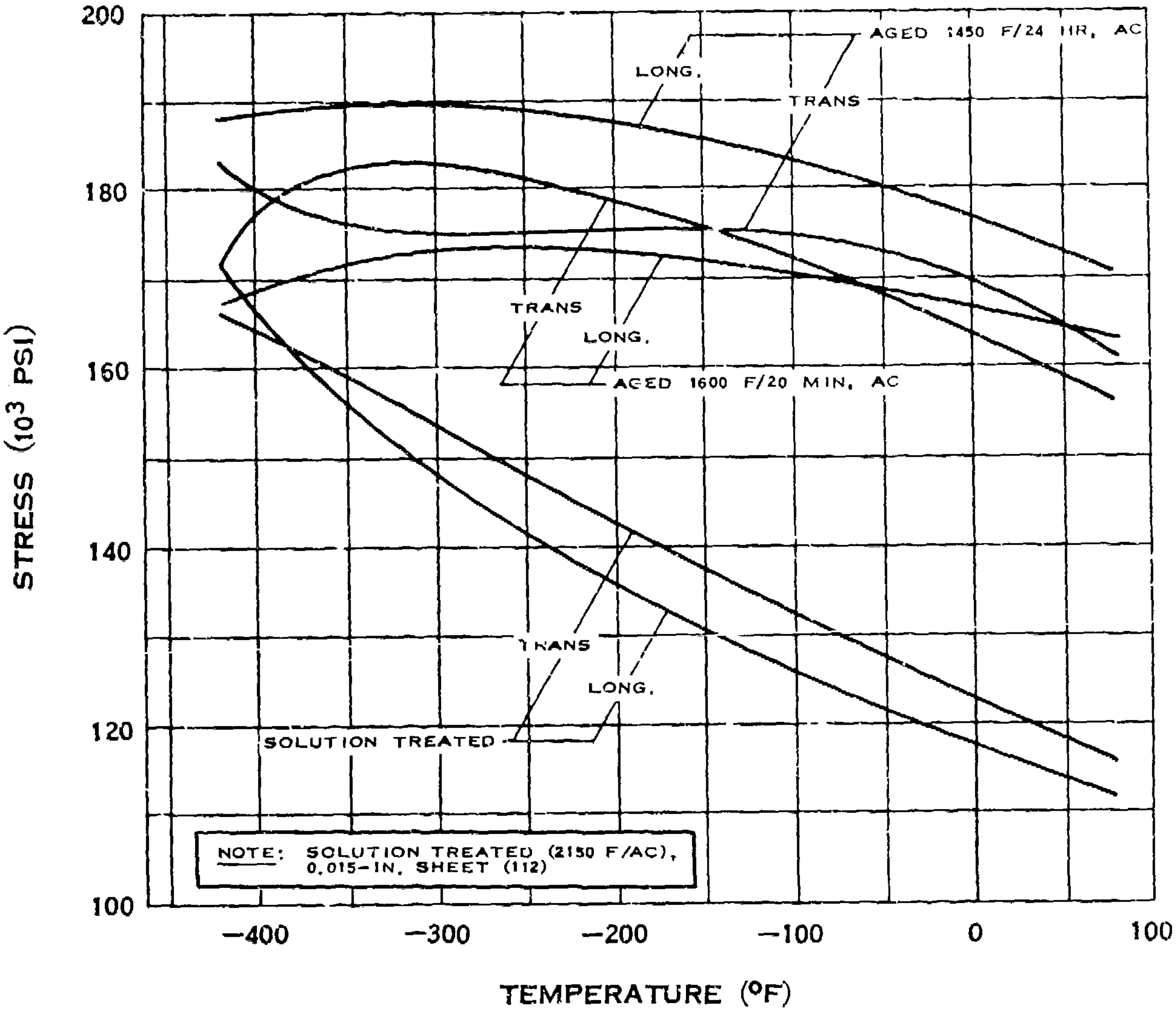
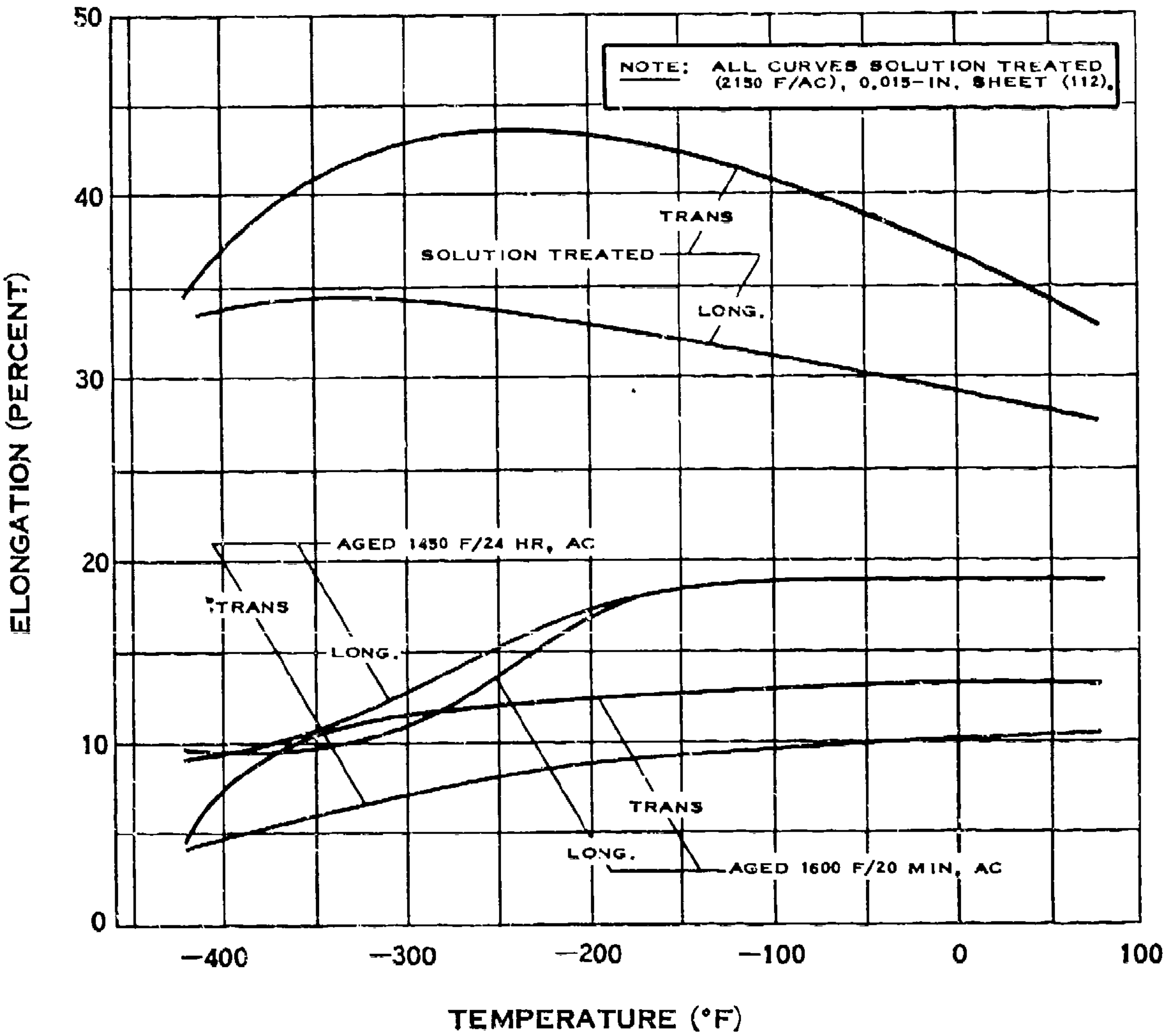
D.10.b



TENSILE STRENGTH OF R-235

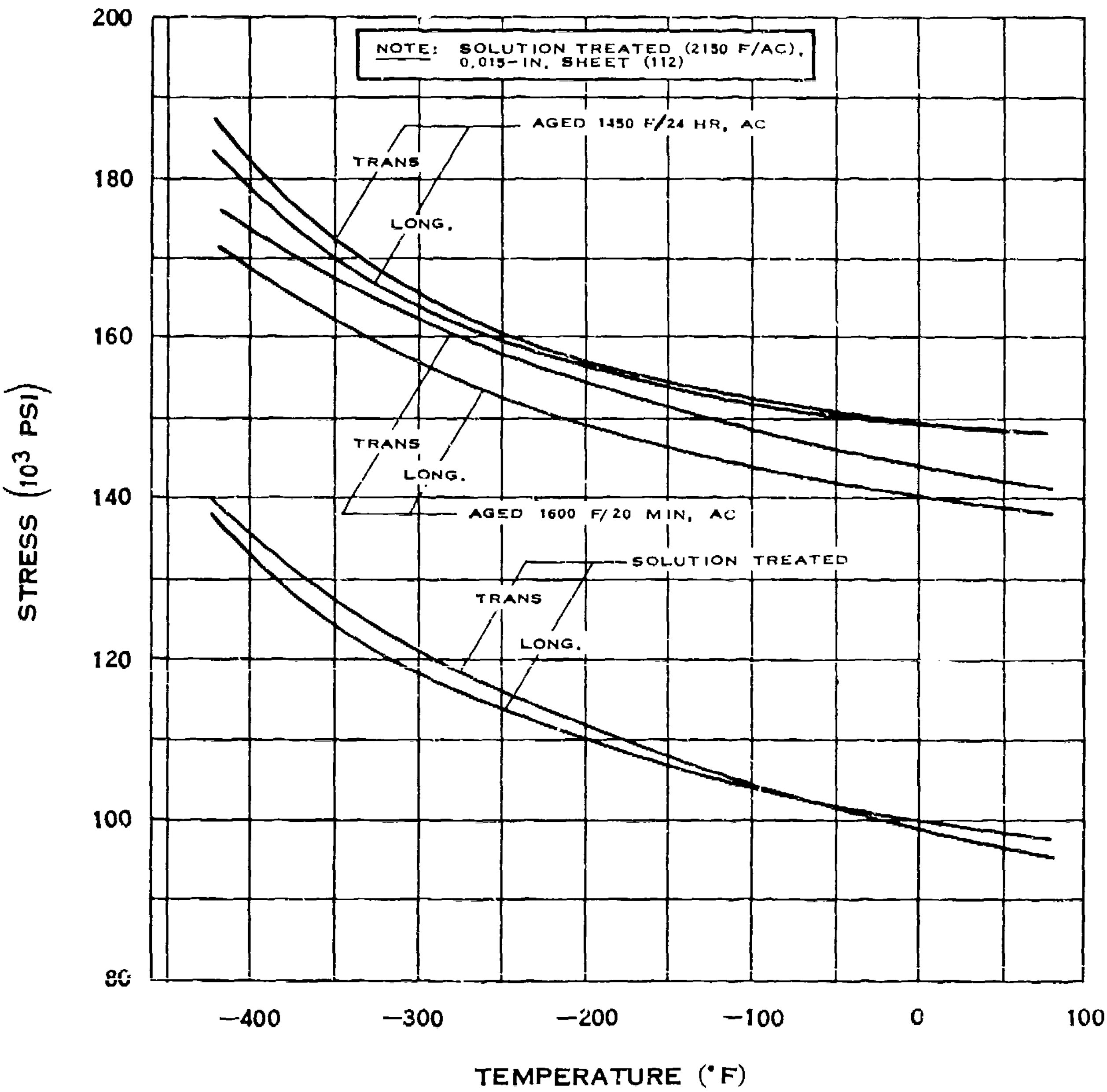
D.10.c



ELONGATION OF R-235

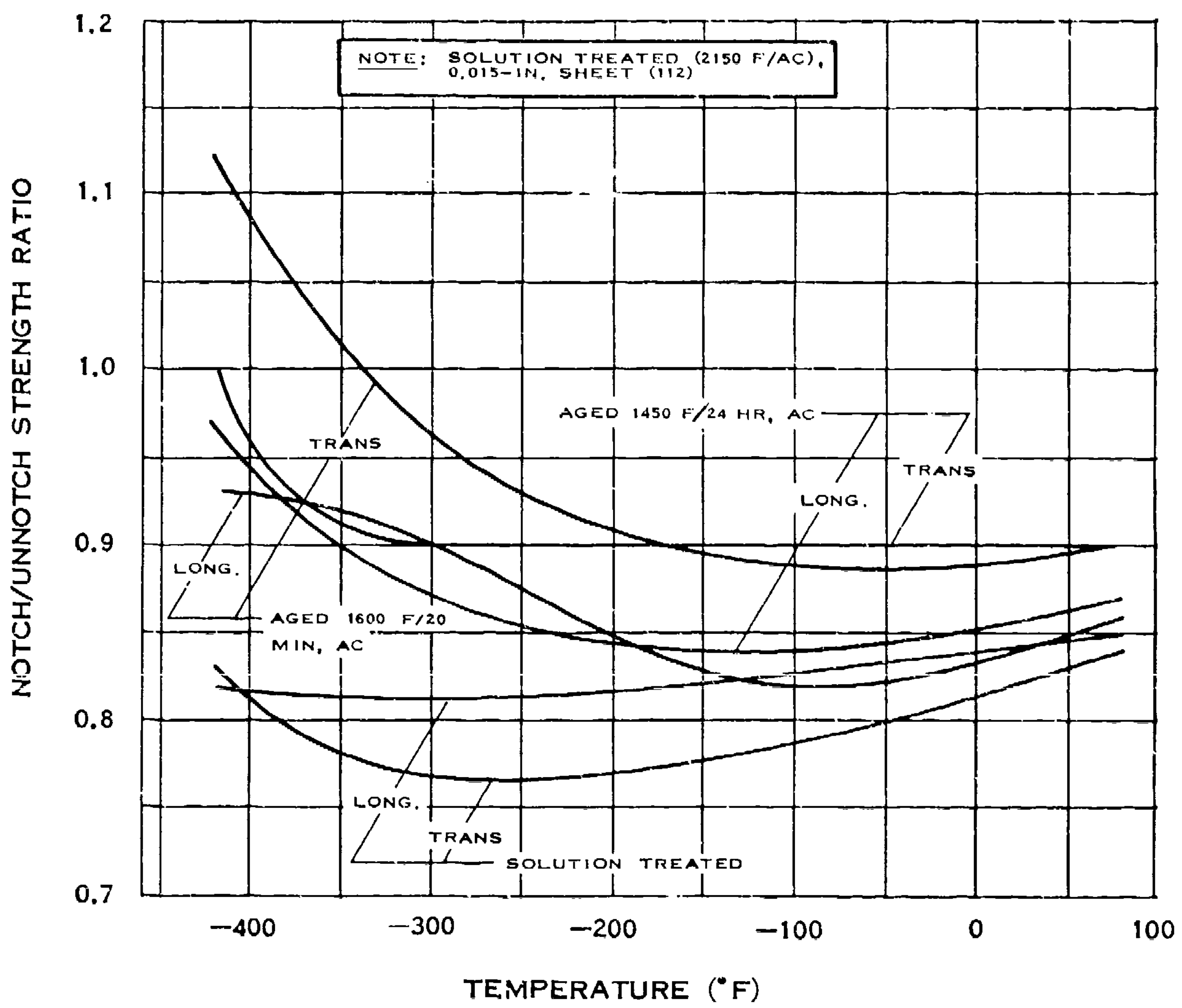
(7-65)

D.10.e



NOTCH TENSILE STRENGTH OF R-235

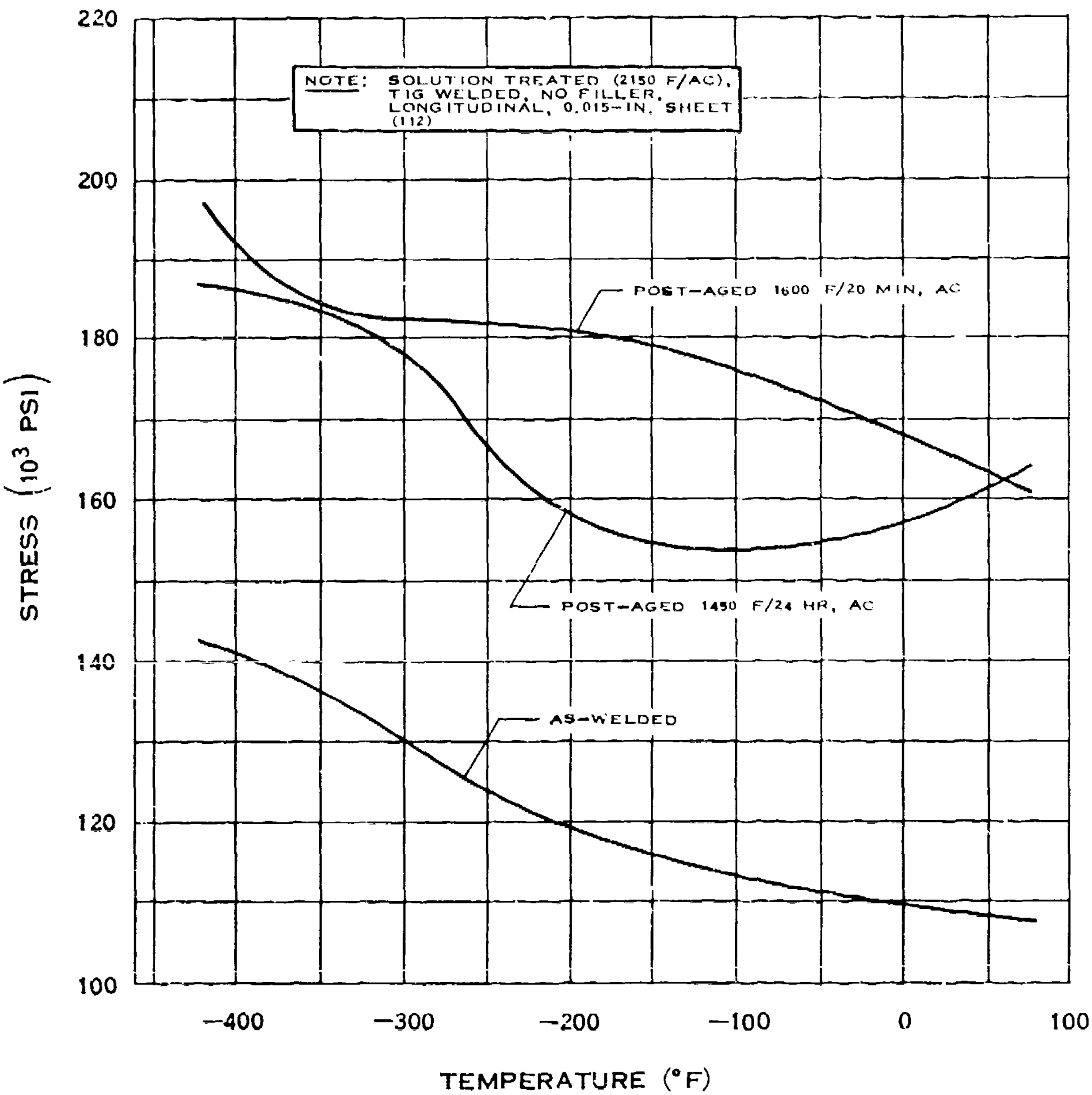
(7-64)



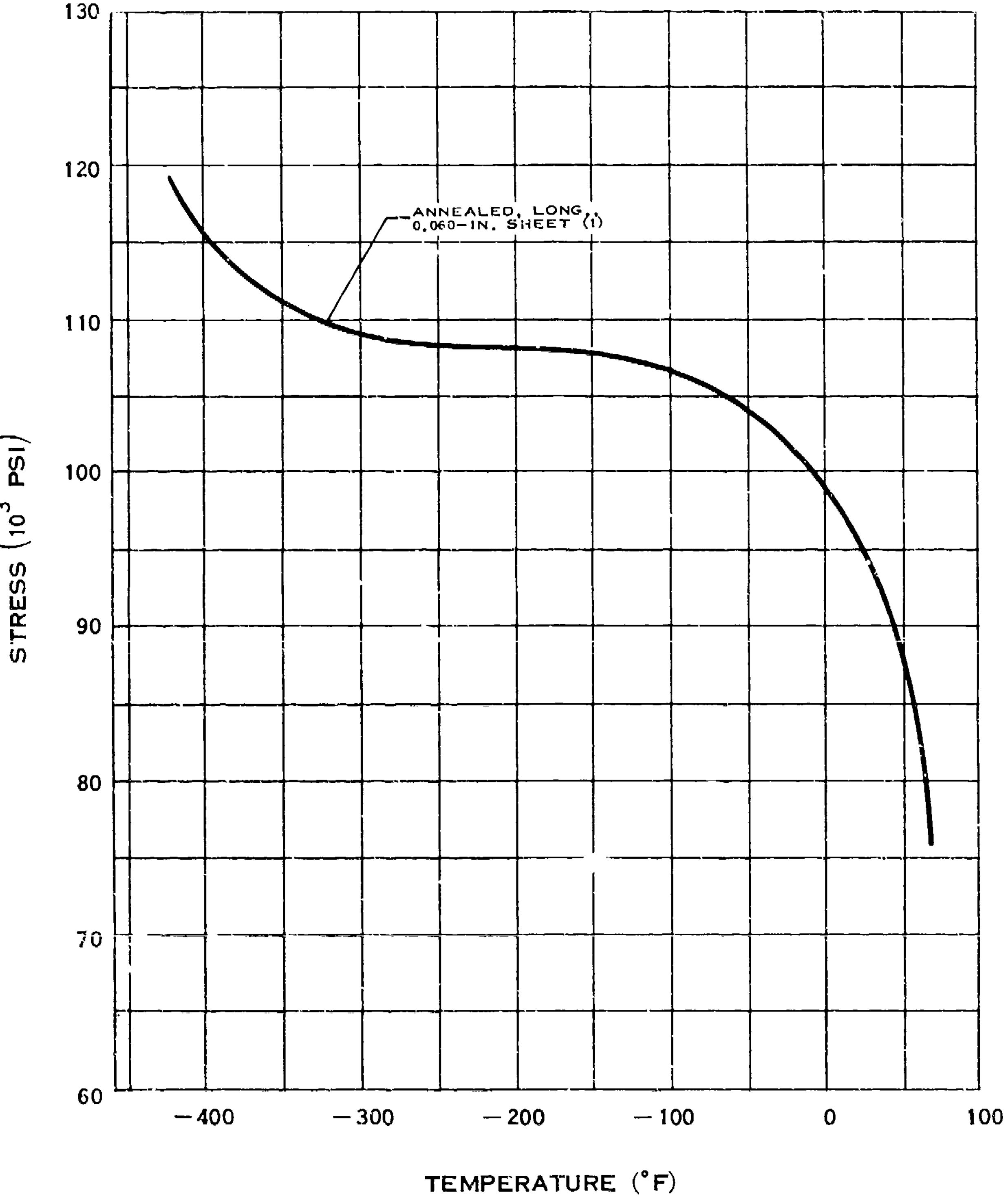
NOTCH STRENGTH RATIO OF R-235

(7−64)

D.10.g

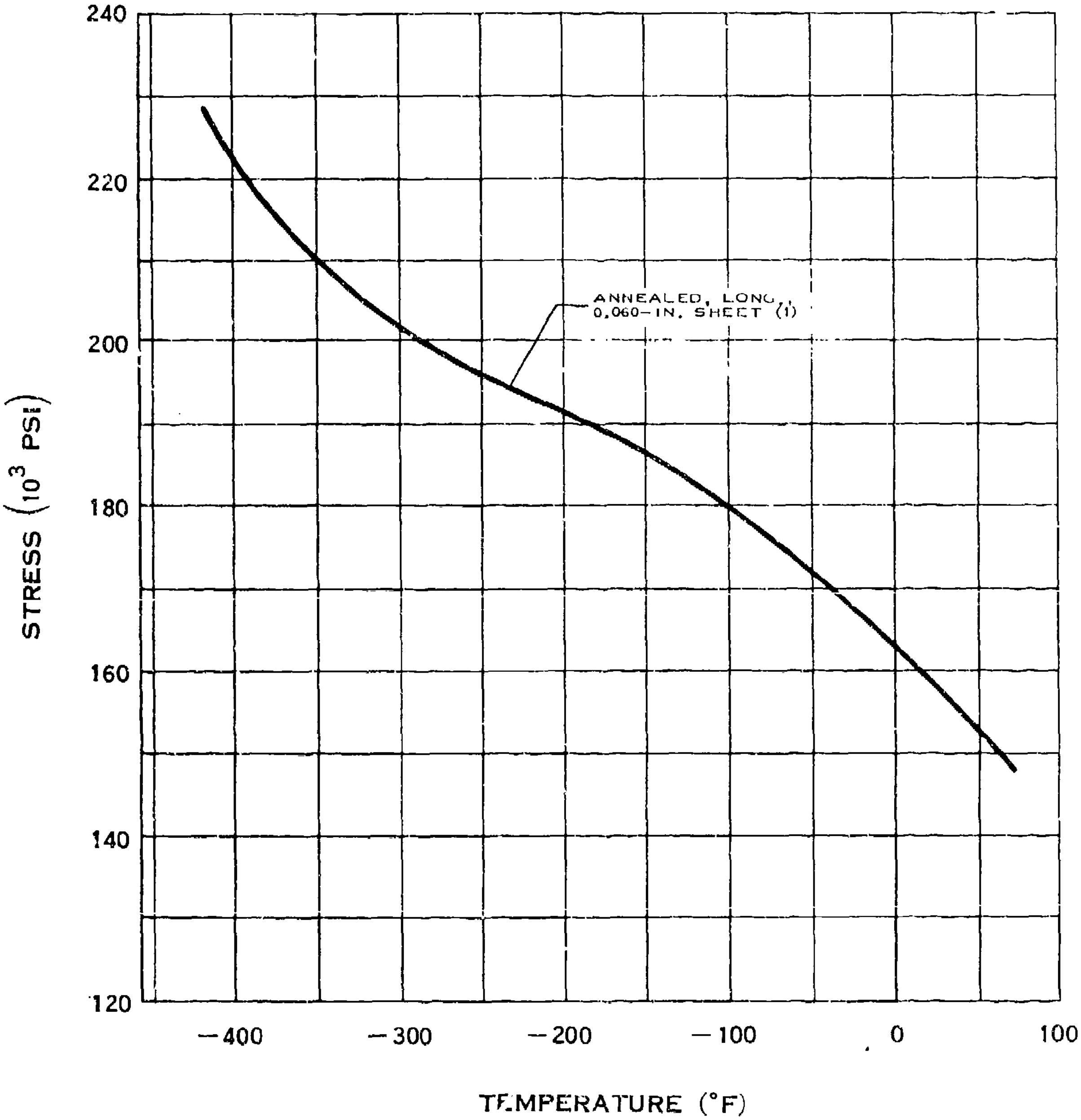


WELD TENSILE STRENGTH OF R-235



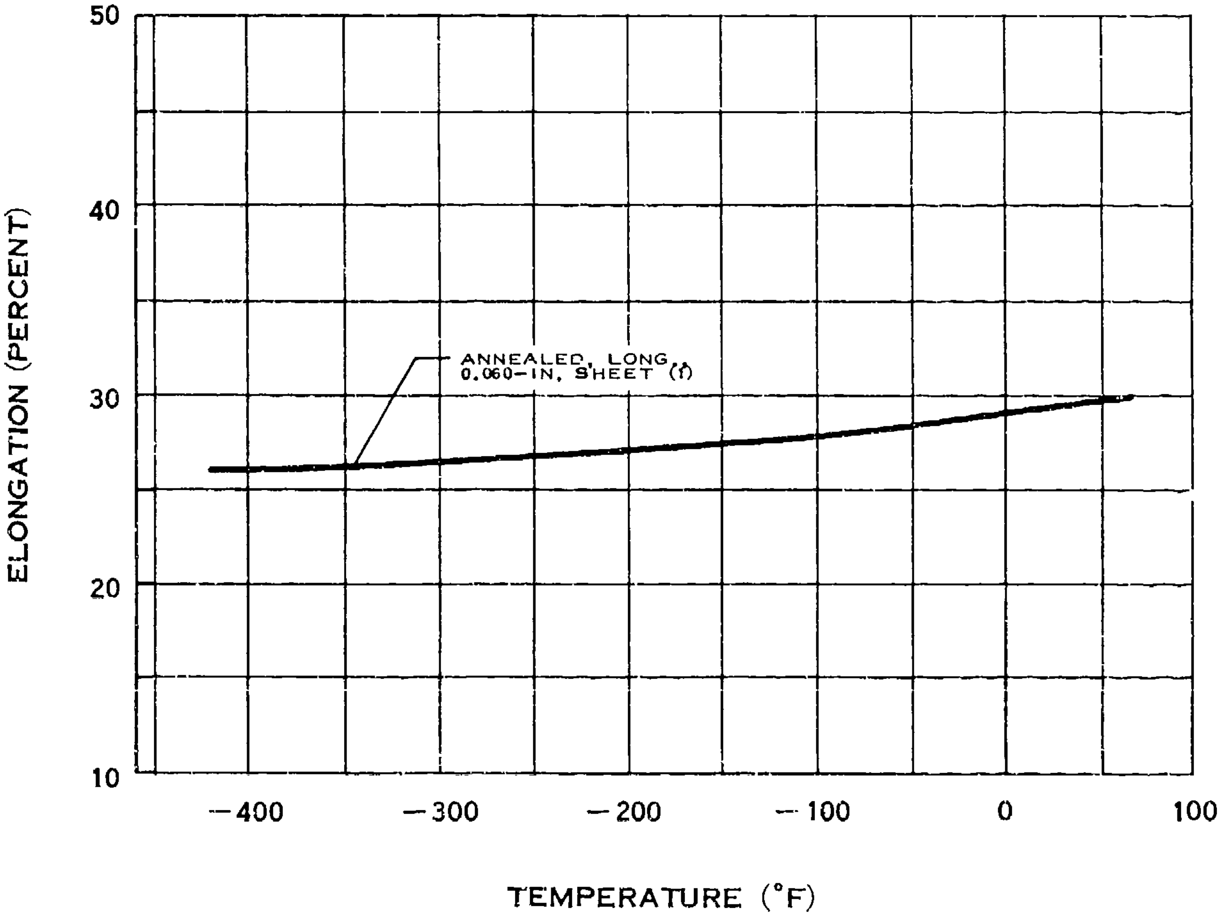
YIELD STRENGTH OF D-979

D.11.b



TENSILE STRENGTH OF D-979

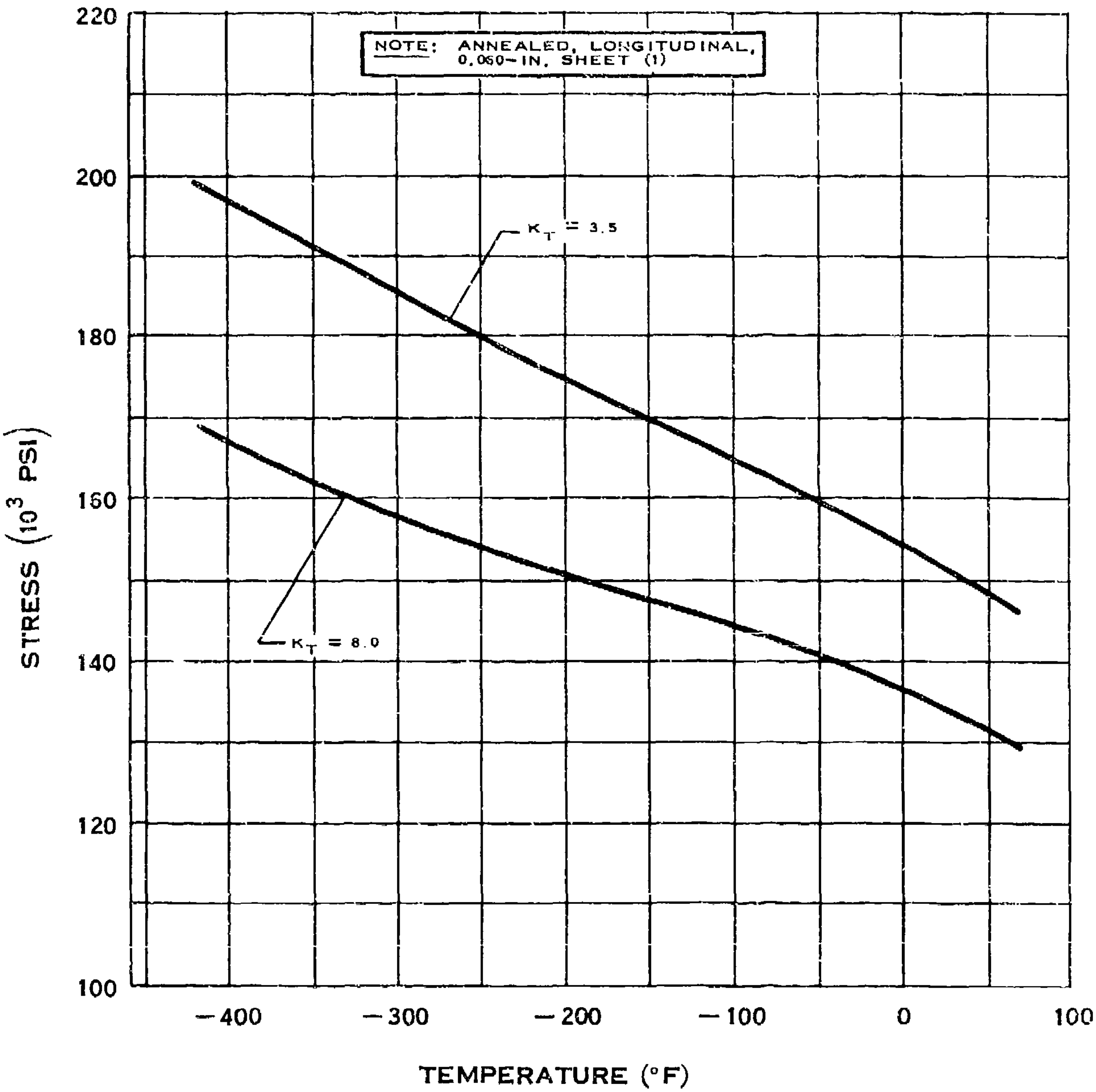
D.11.c



ELONGATION OF D-979

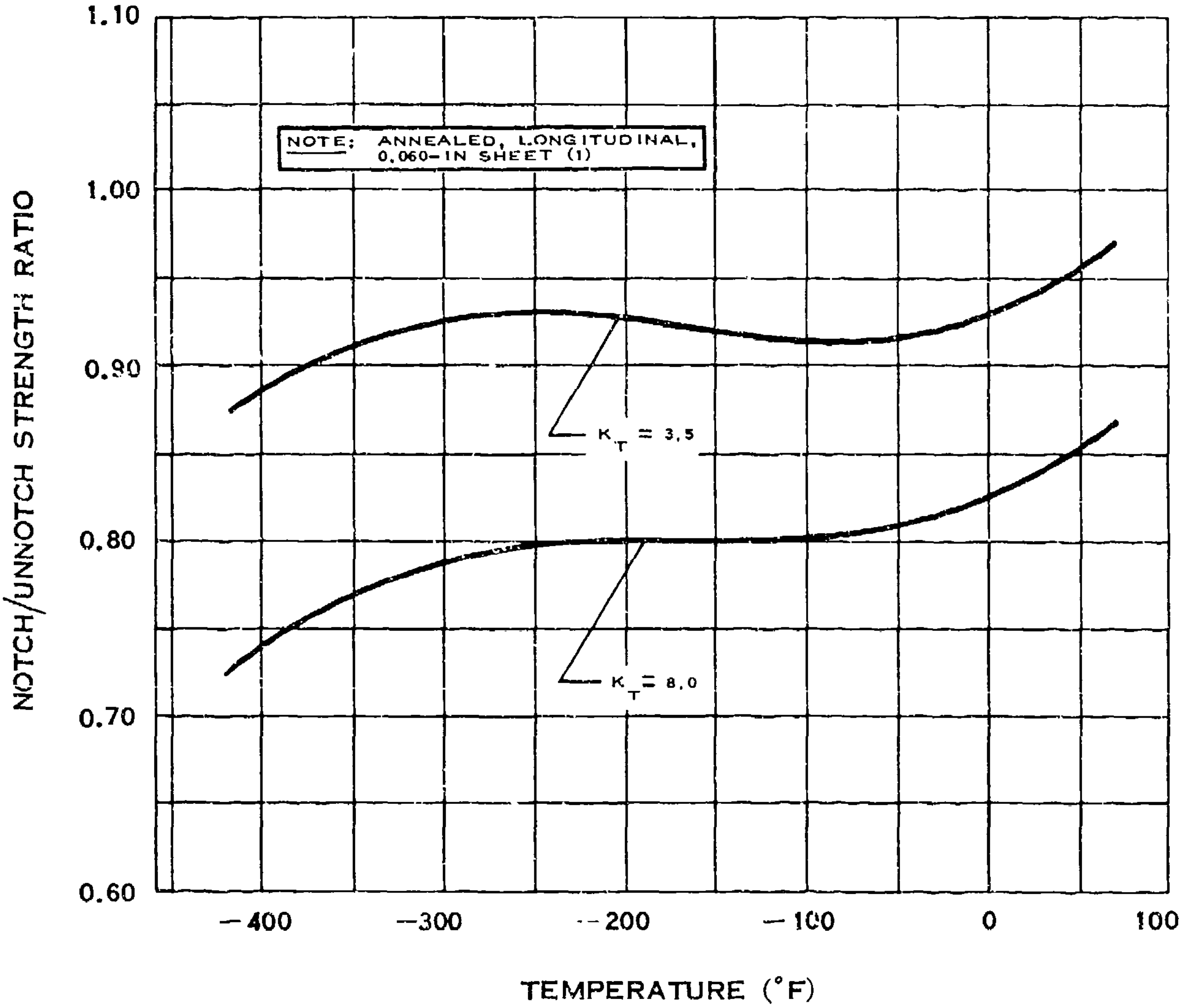
(7-64)

D.11.e

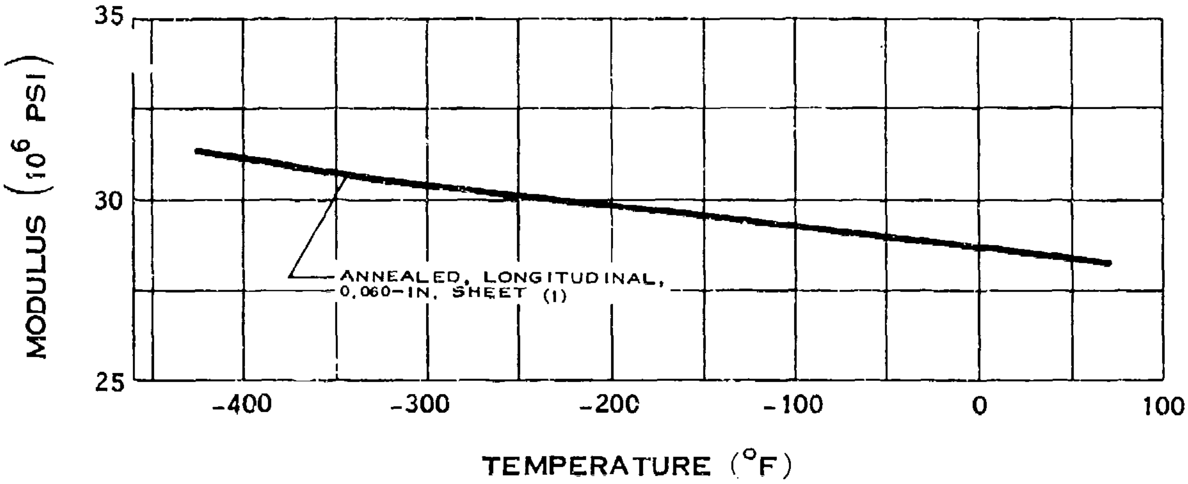


NOTCH TENSILE STRENGTH OF D-979

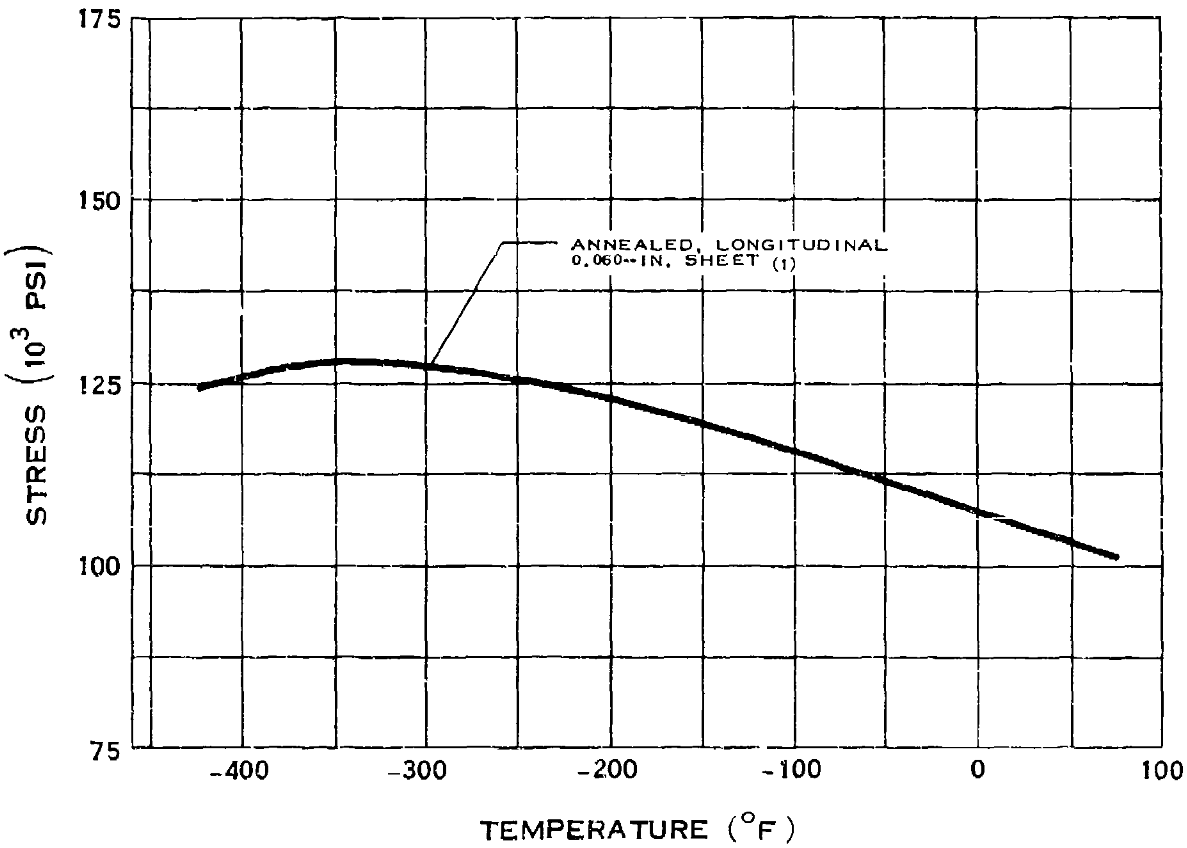
D.11.e-1



NOTCH STRENGTH RATIO OF D-979

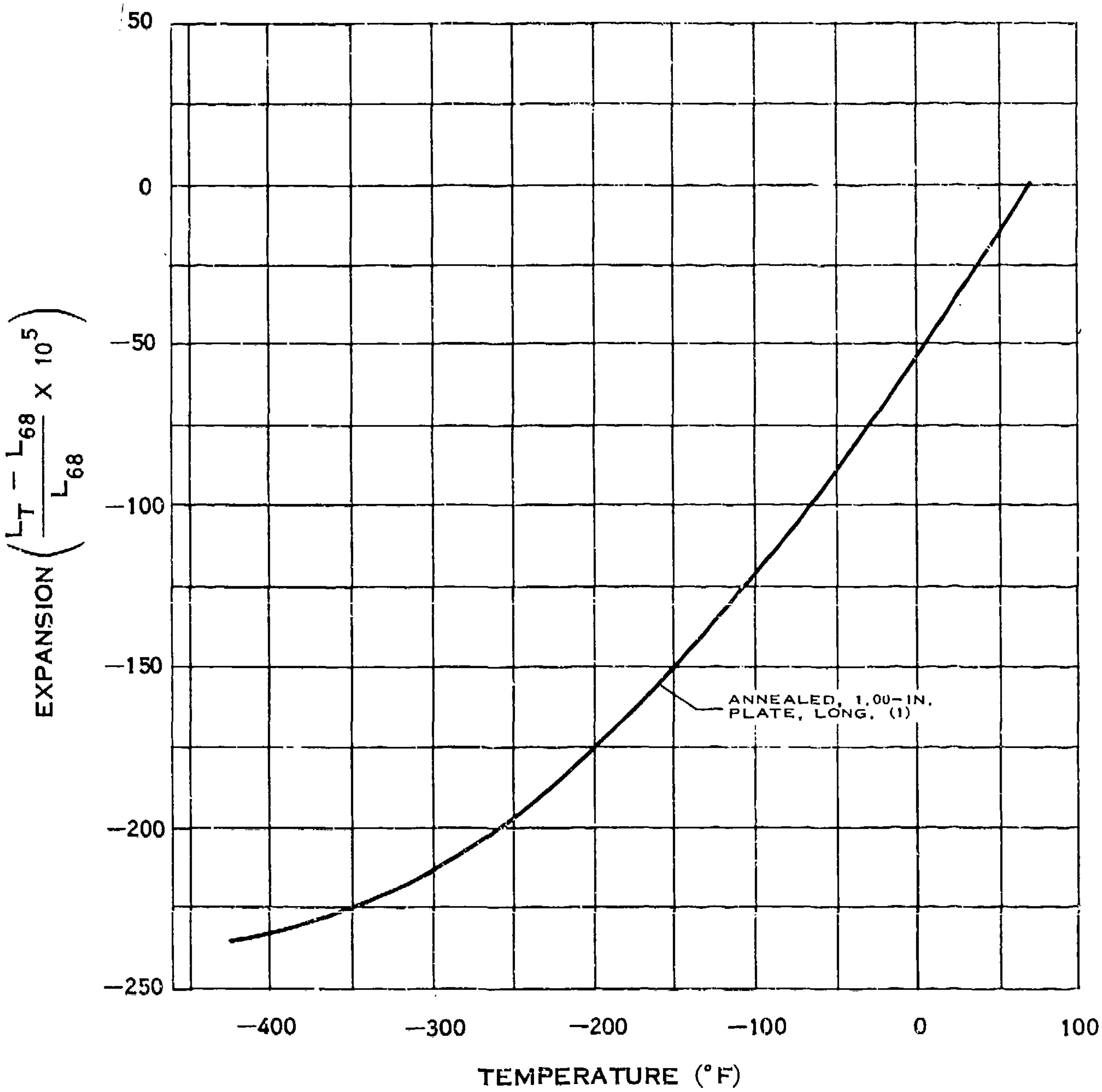


MODULUS OF ELASTICITY OF D-979



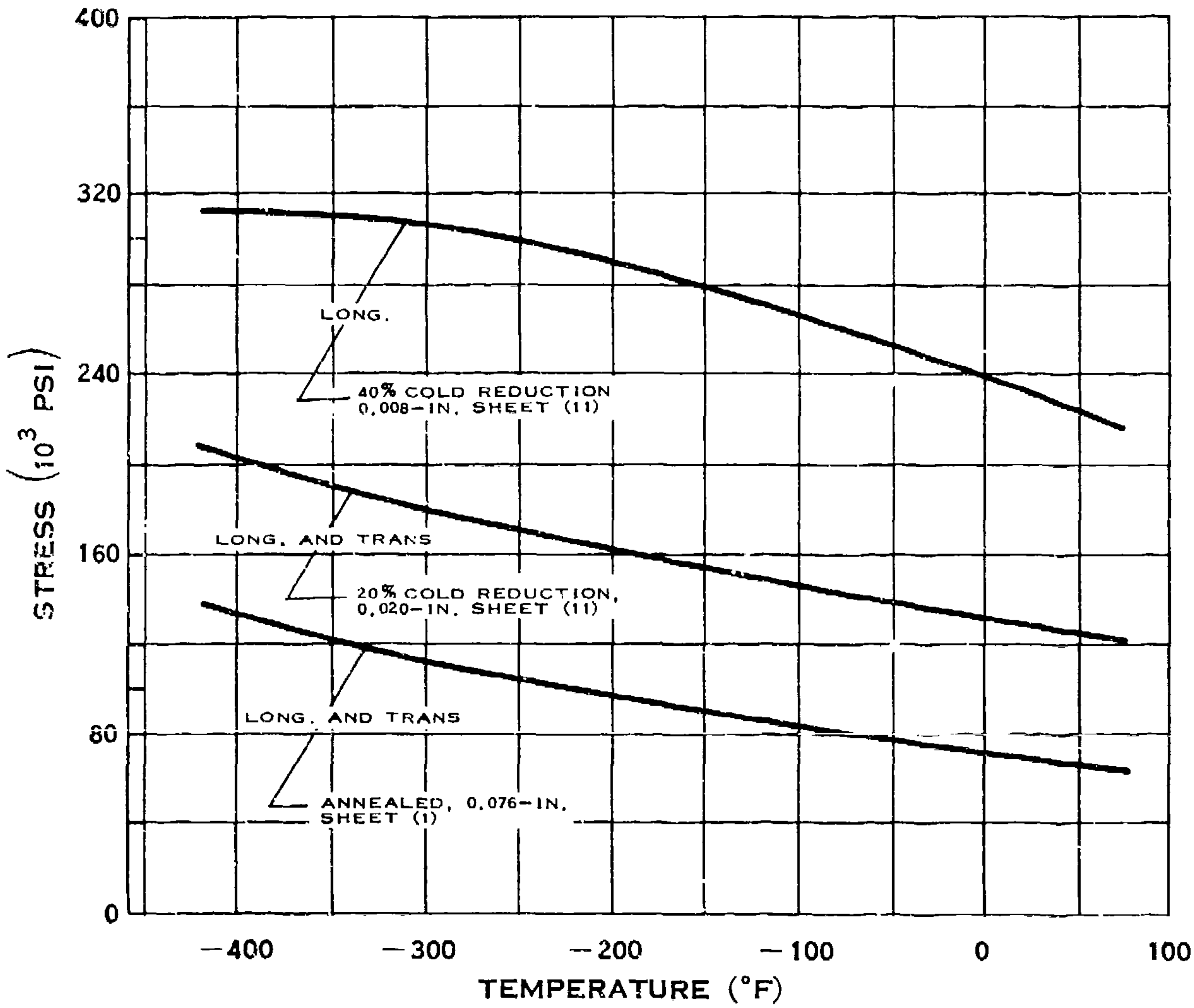
SHEAR STRENGTH OF D-979

(7-64)



THERMAL EXPANSION OF D-979

D.12.a



YIELD STRENGTH OF L-605

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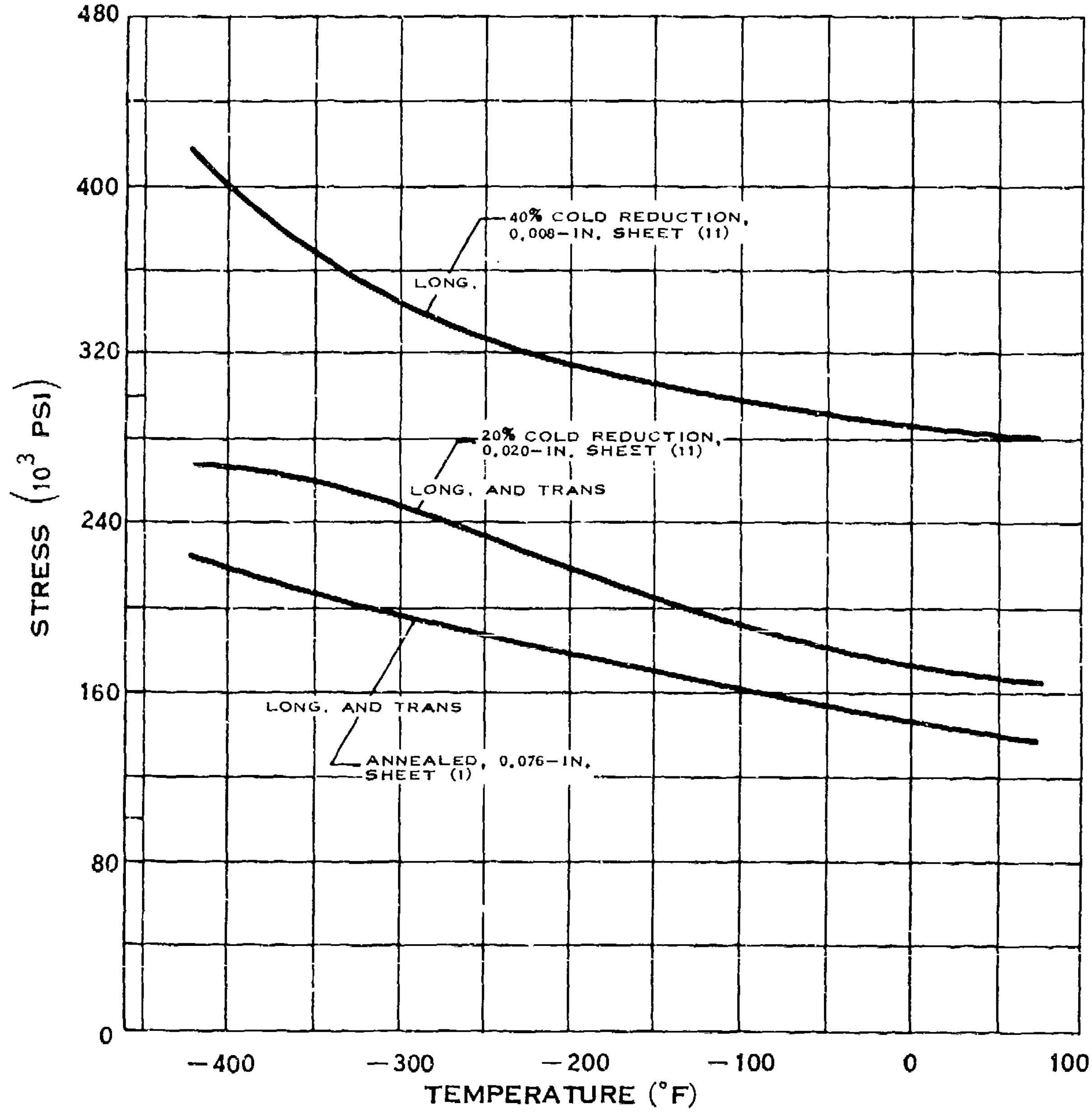
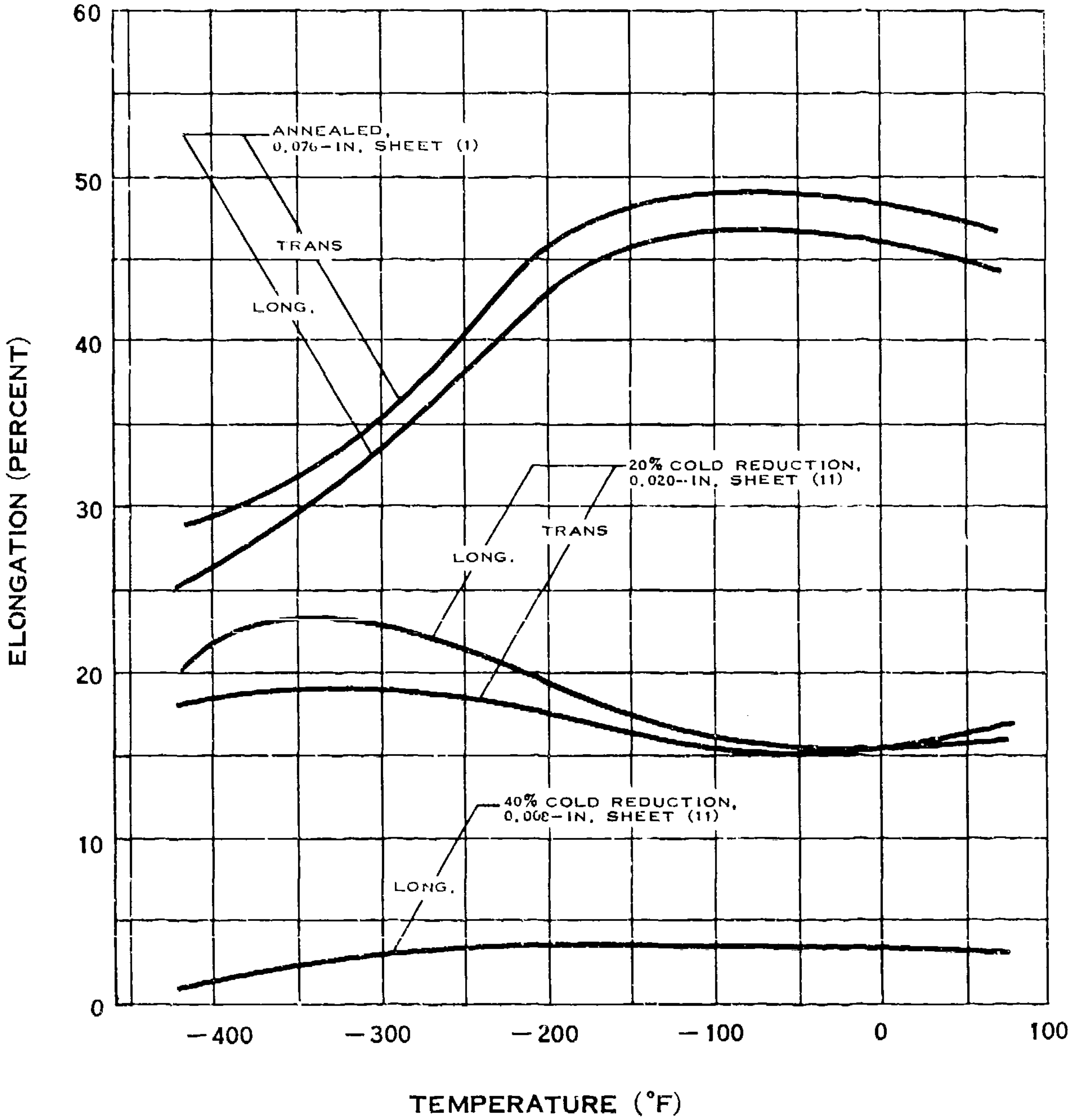
D.12.b



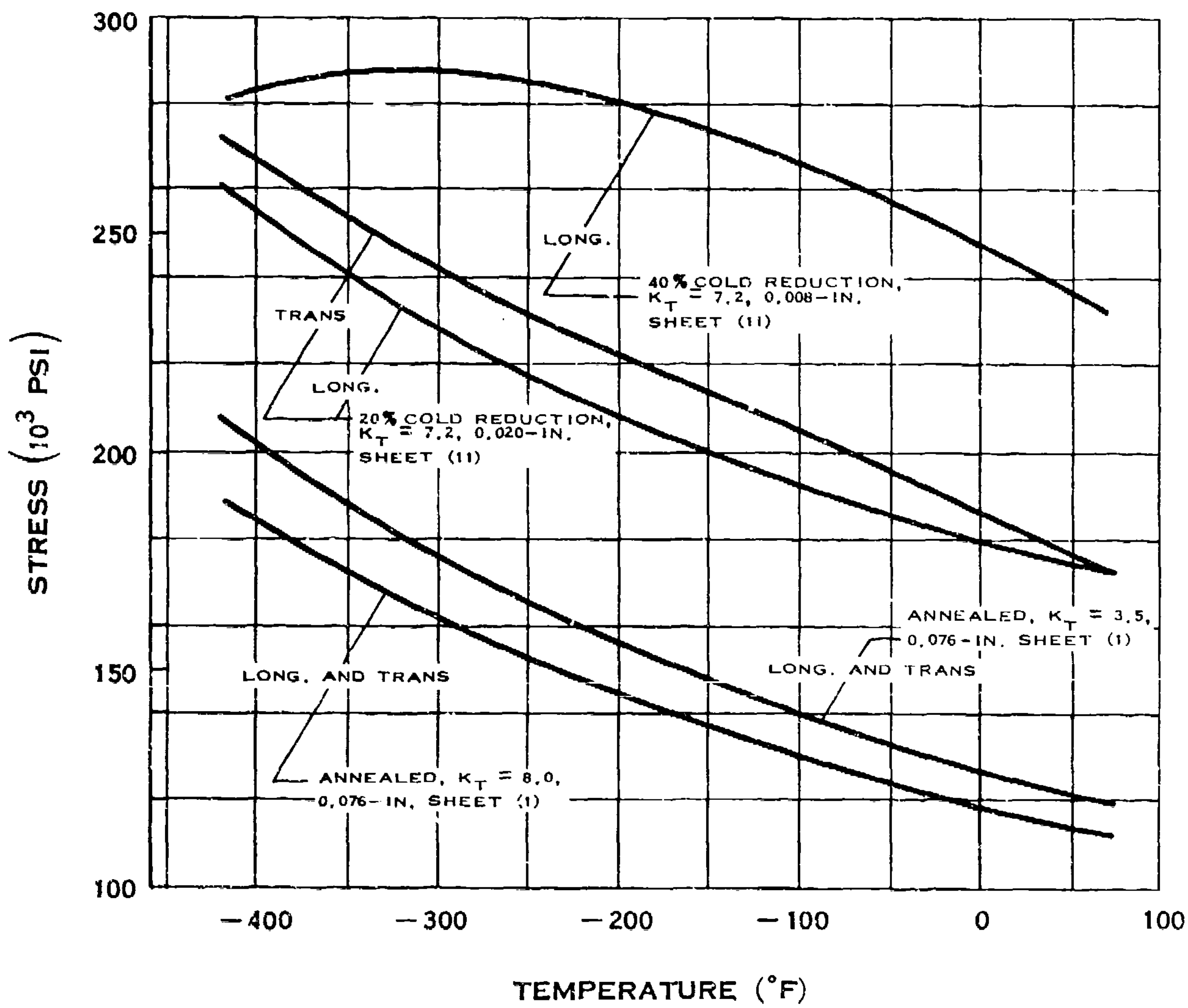
TENSILE STRENGTH OF L-605



ELONGATION OF L-605

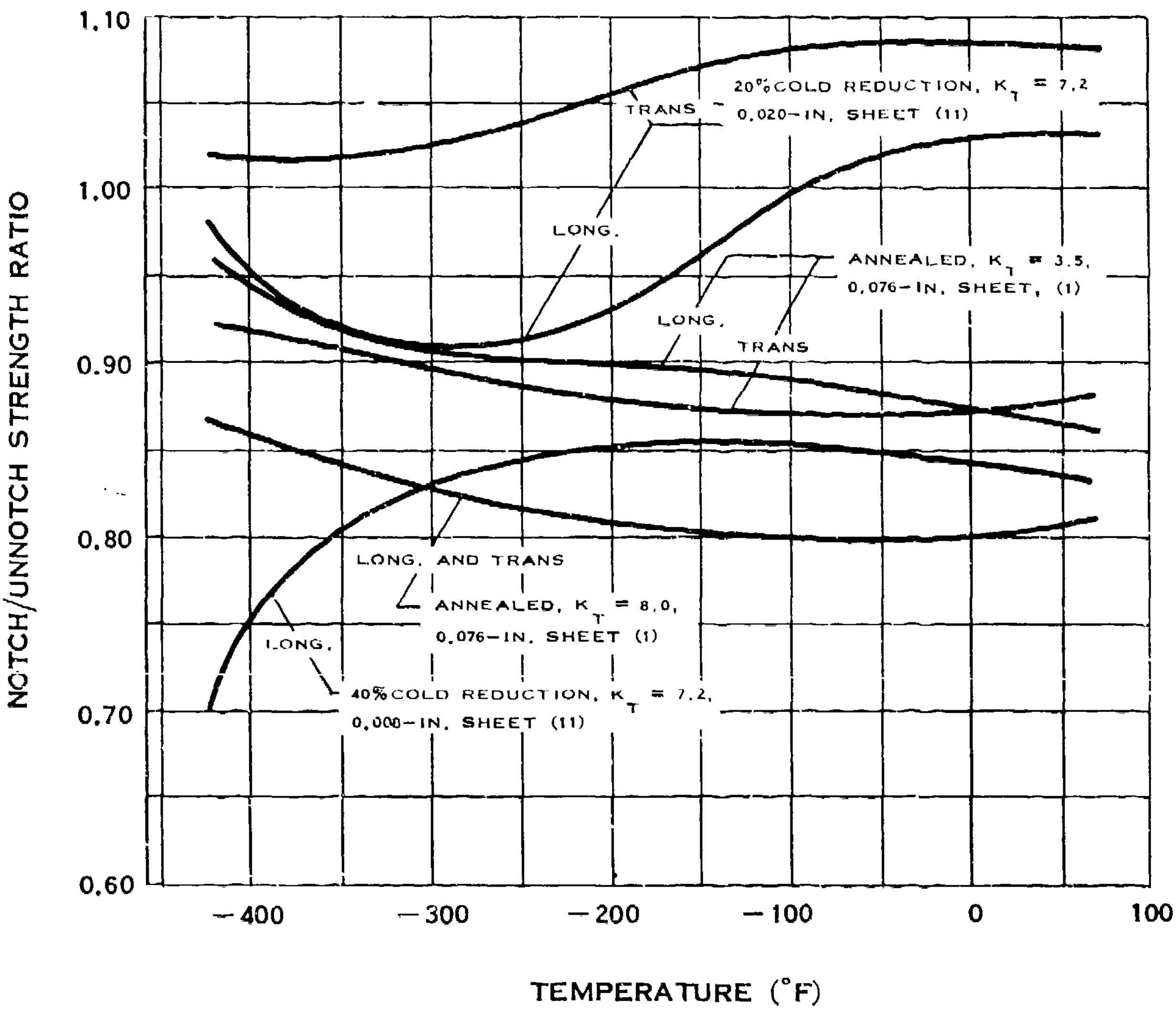
(7-64)

D.12.e



NOTCH TENSILE STRENGTH OF L-605

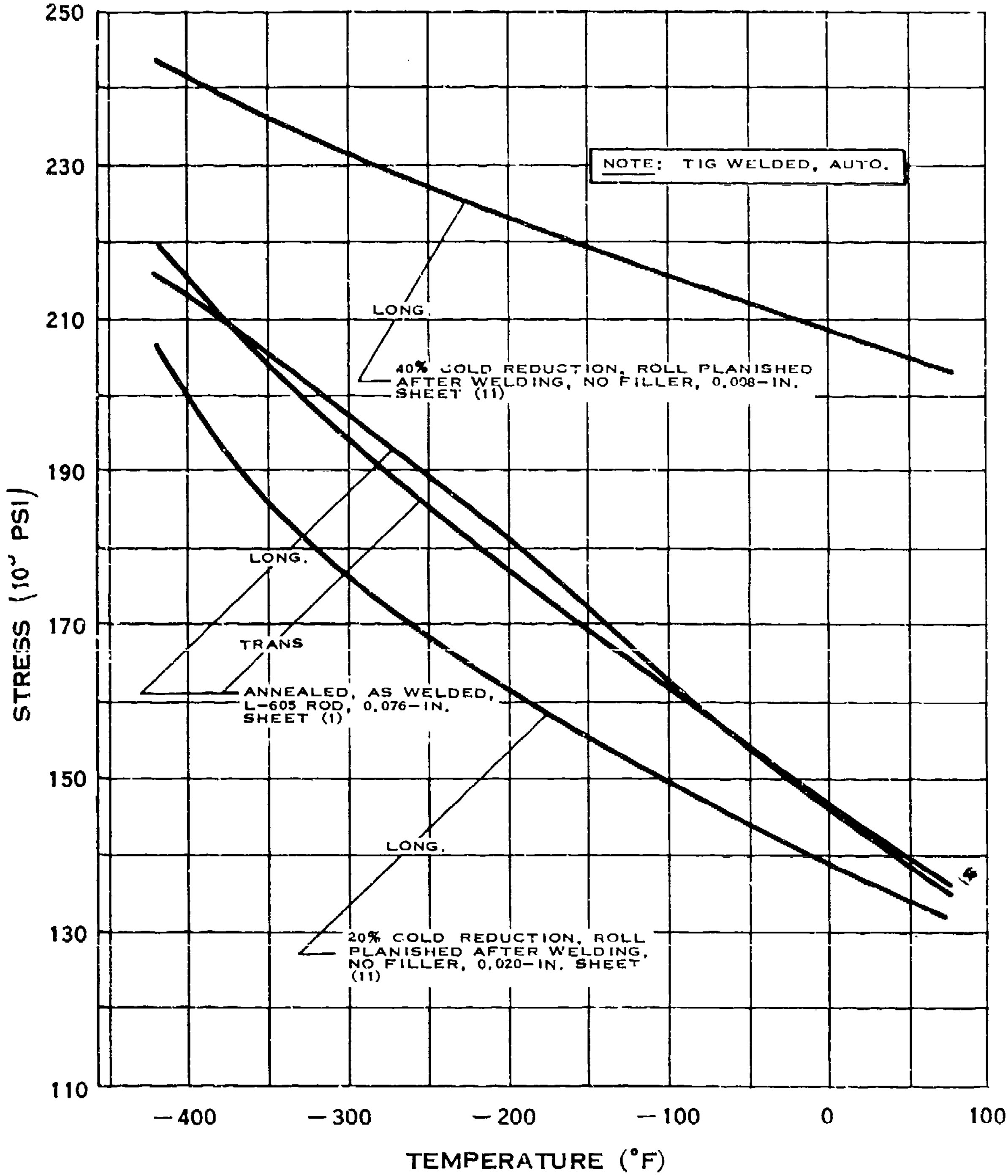
D.12.e-1



NOTCH STRENGTH RATIO OF L-605

(7-64)

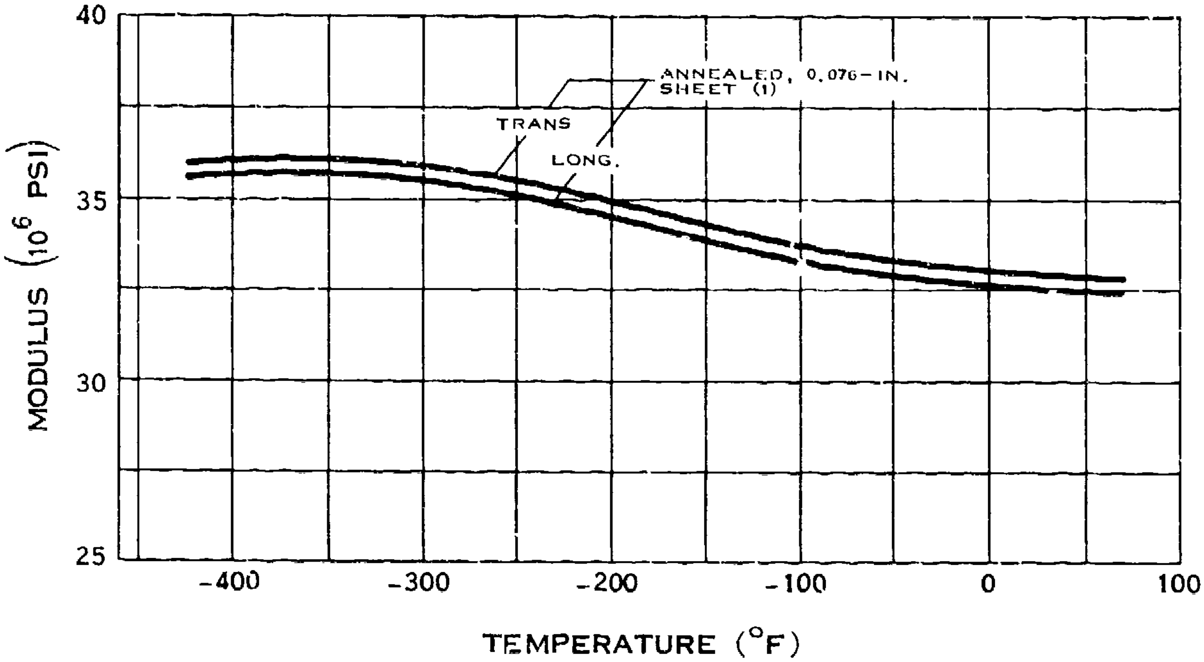
D.12.g



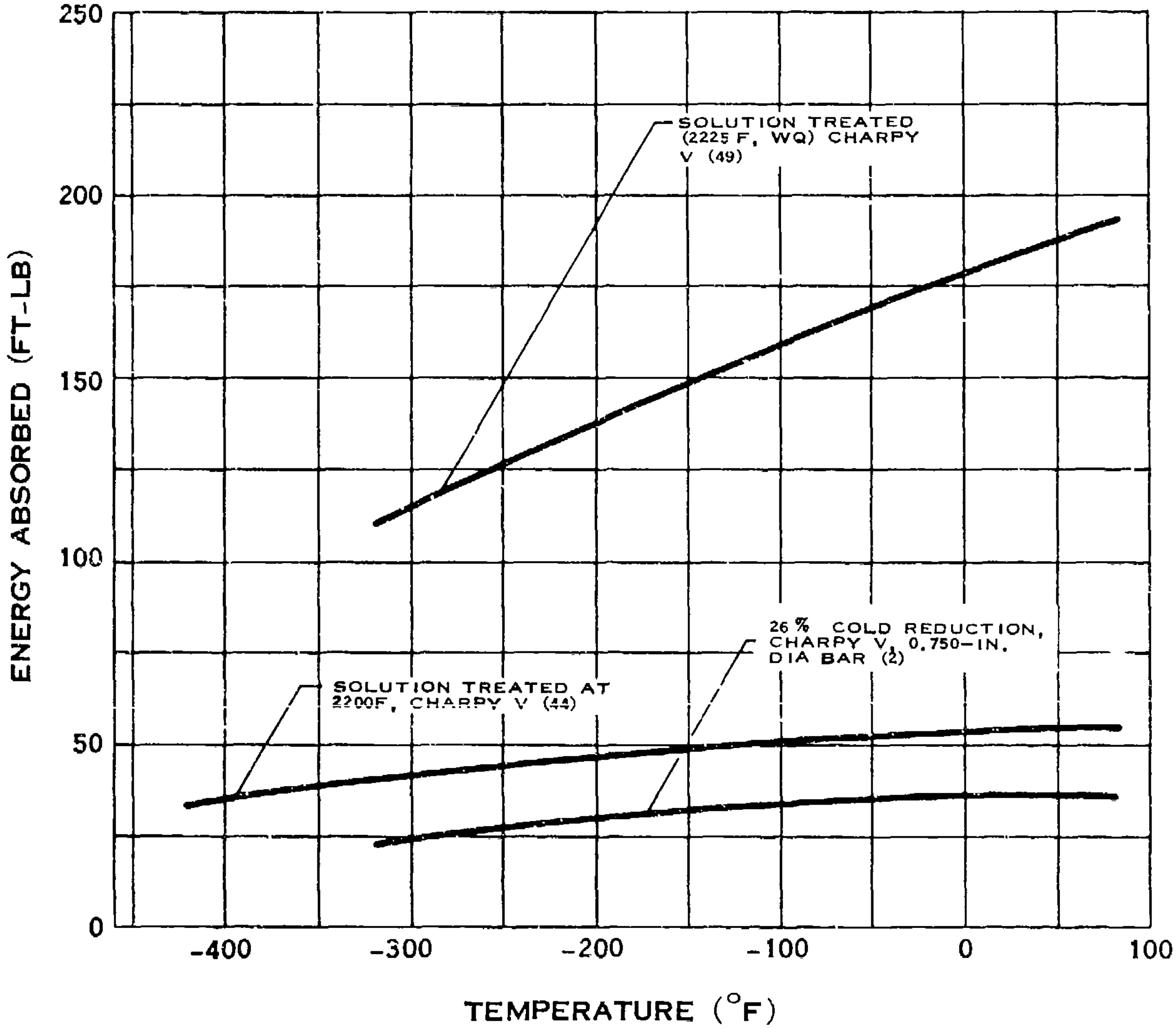
(7−64)

WELD TENSILE STRENGTH OF L-605

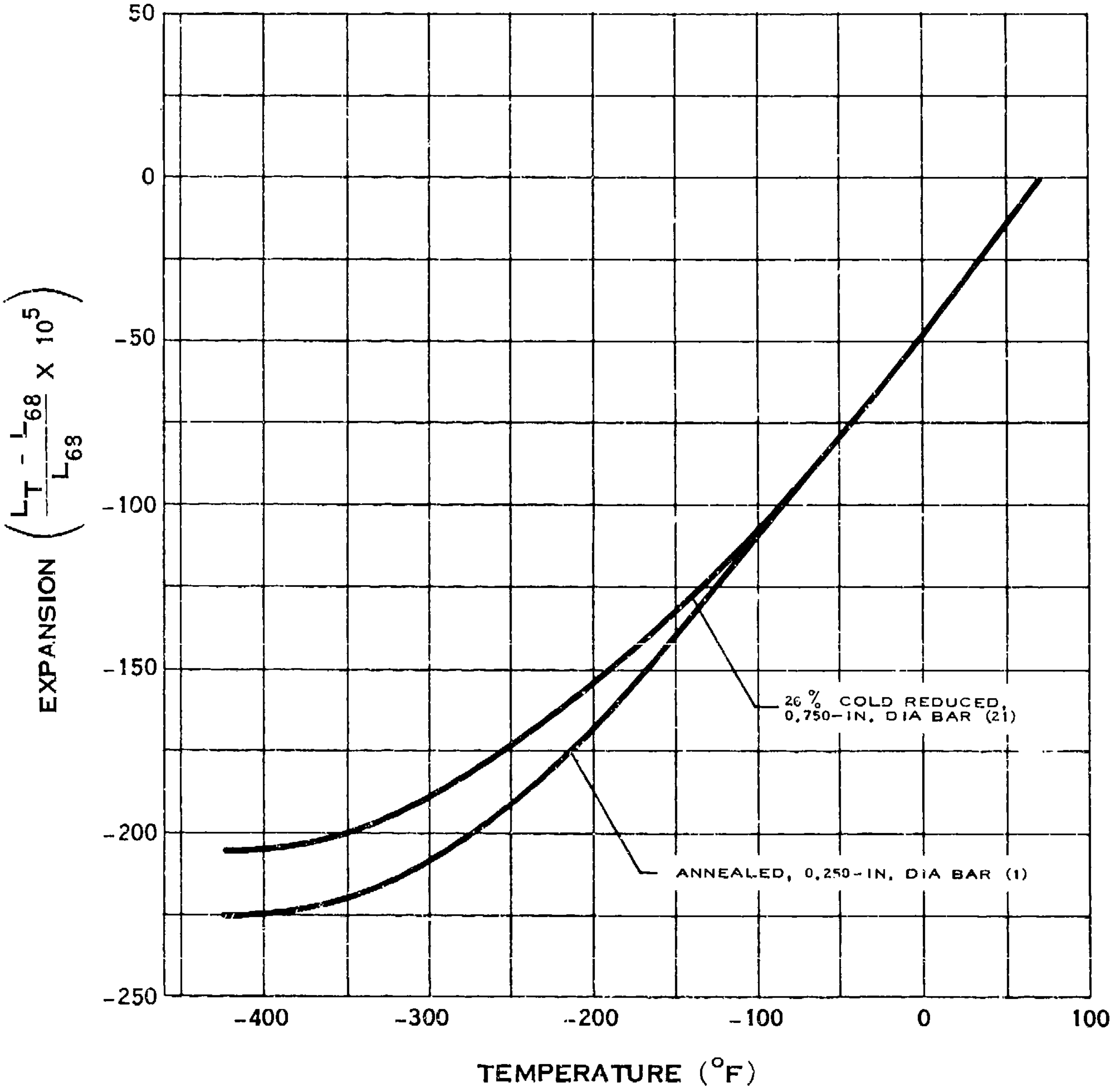
D.12.i



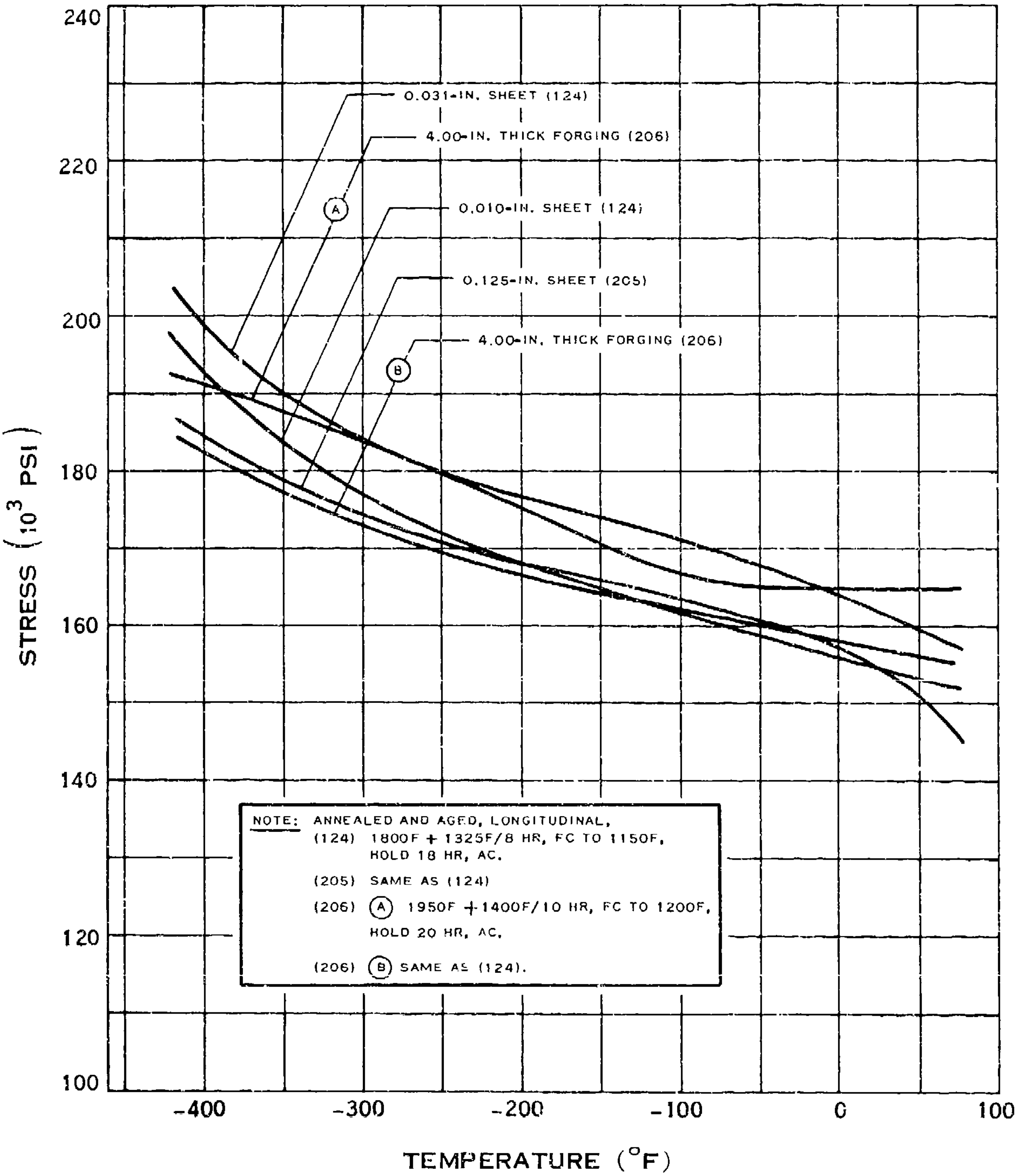
MODULUS OF ELASTICITY OF L-605



IMPACT STRENGTH OF L-605



THERMAL EXPANSION OF L-605



YIELD STRENGTH OF INCONEL 718

(6-68)

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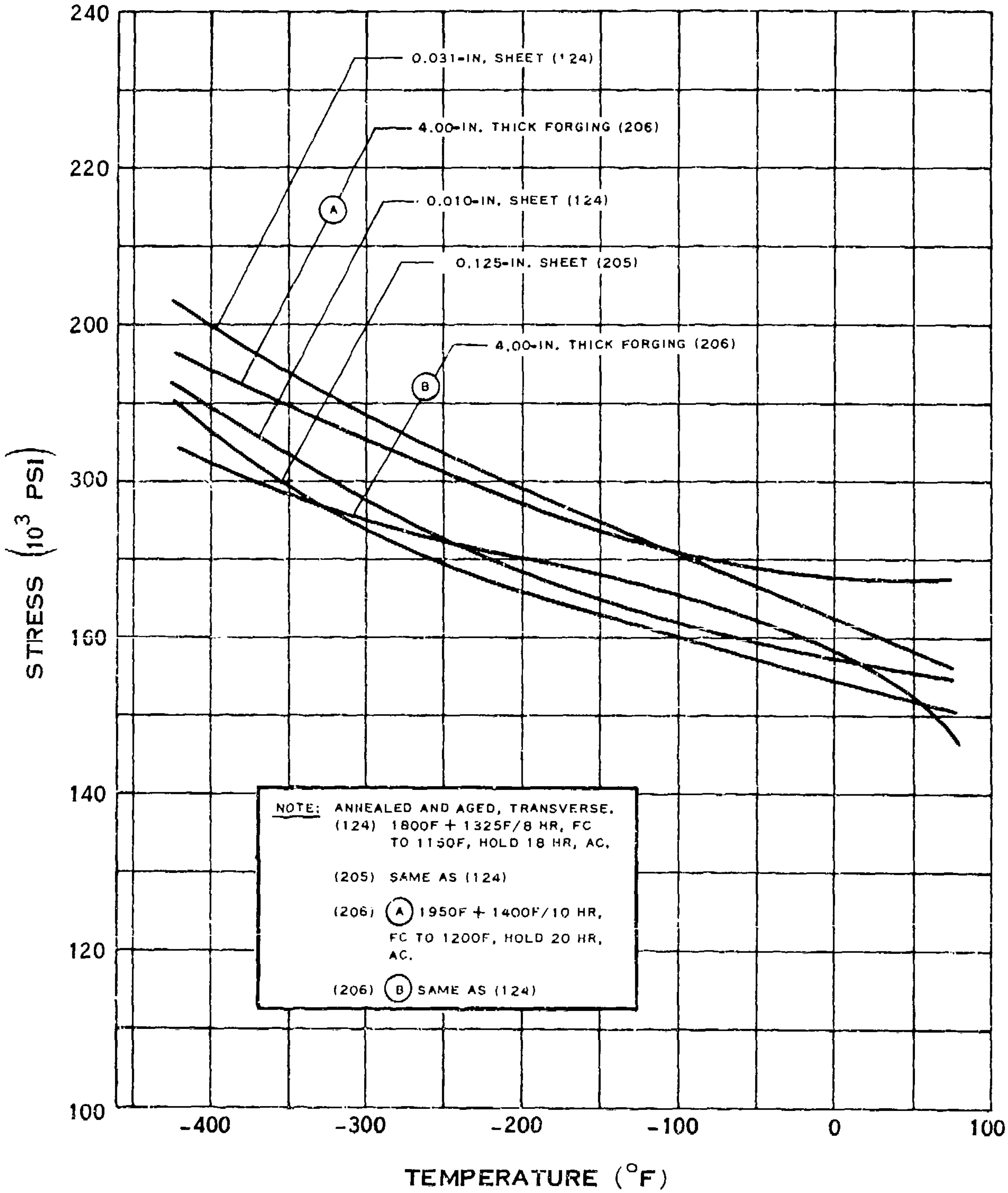
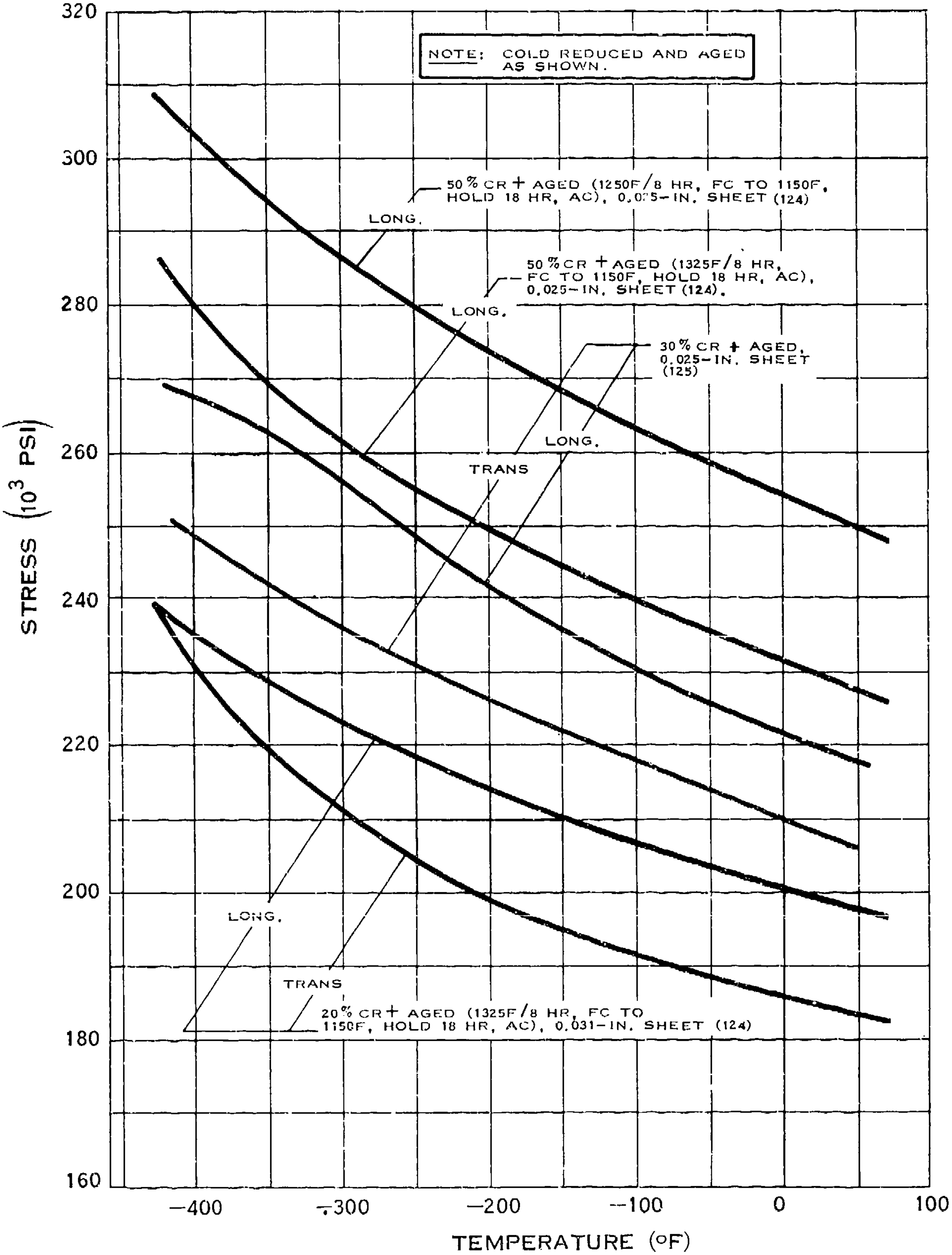
D.13.a-1

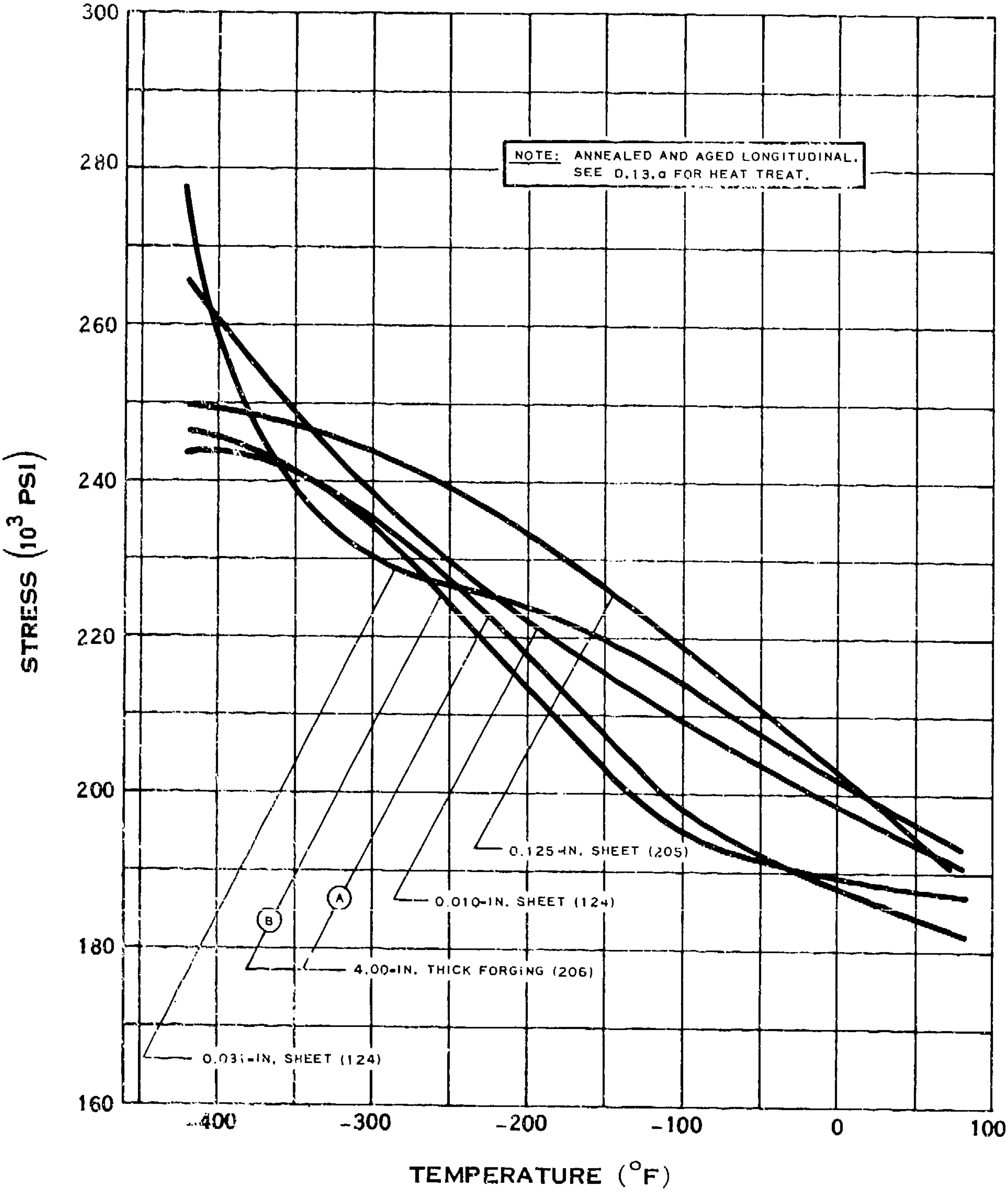


YIELD STRENGTH OF INCONEL 718



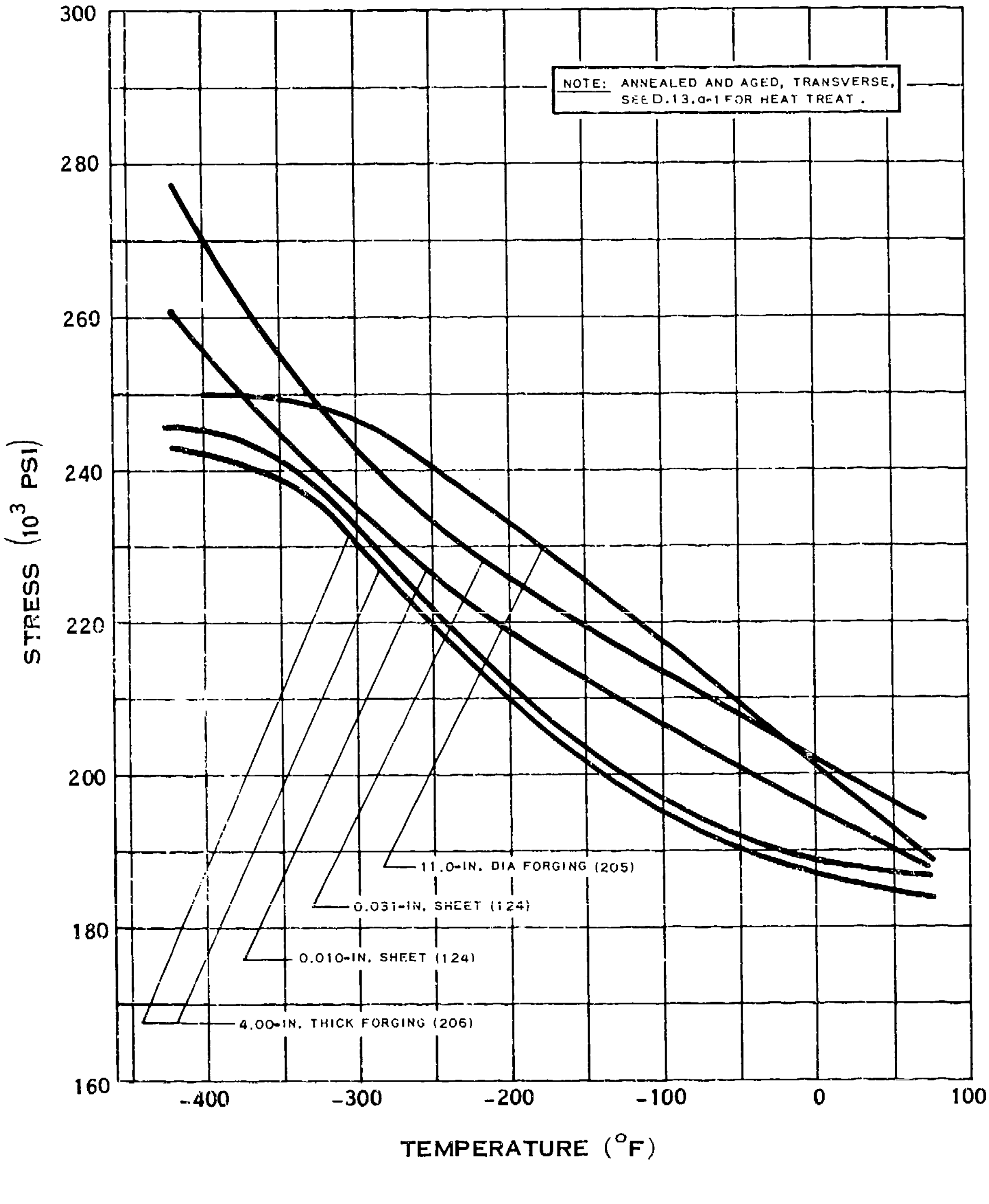
(6-68)

YIELD STRENGTH OF INCONEL 718



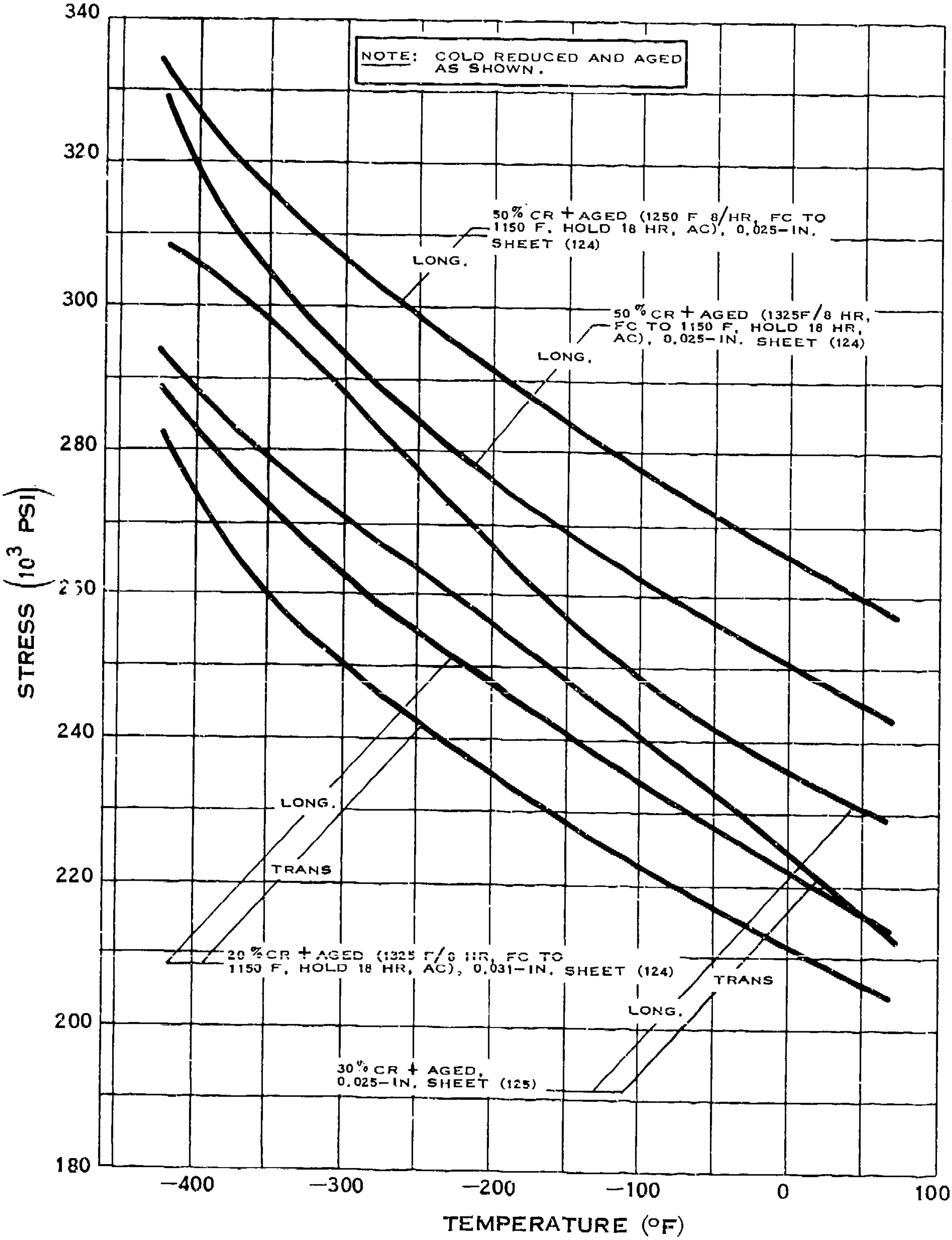
TENSILE STRENGTH OF INCONEL 718

D.13.b-1



TENSILE STRENGTH OF INCONEL 718

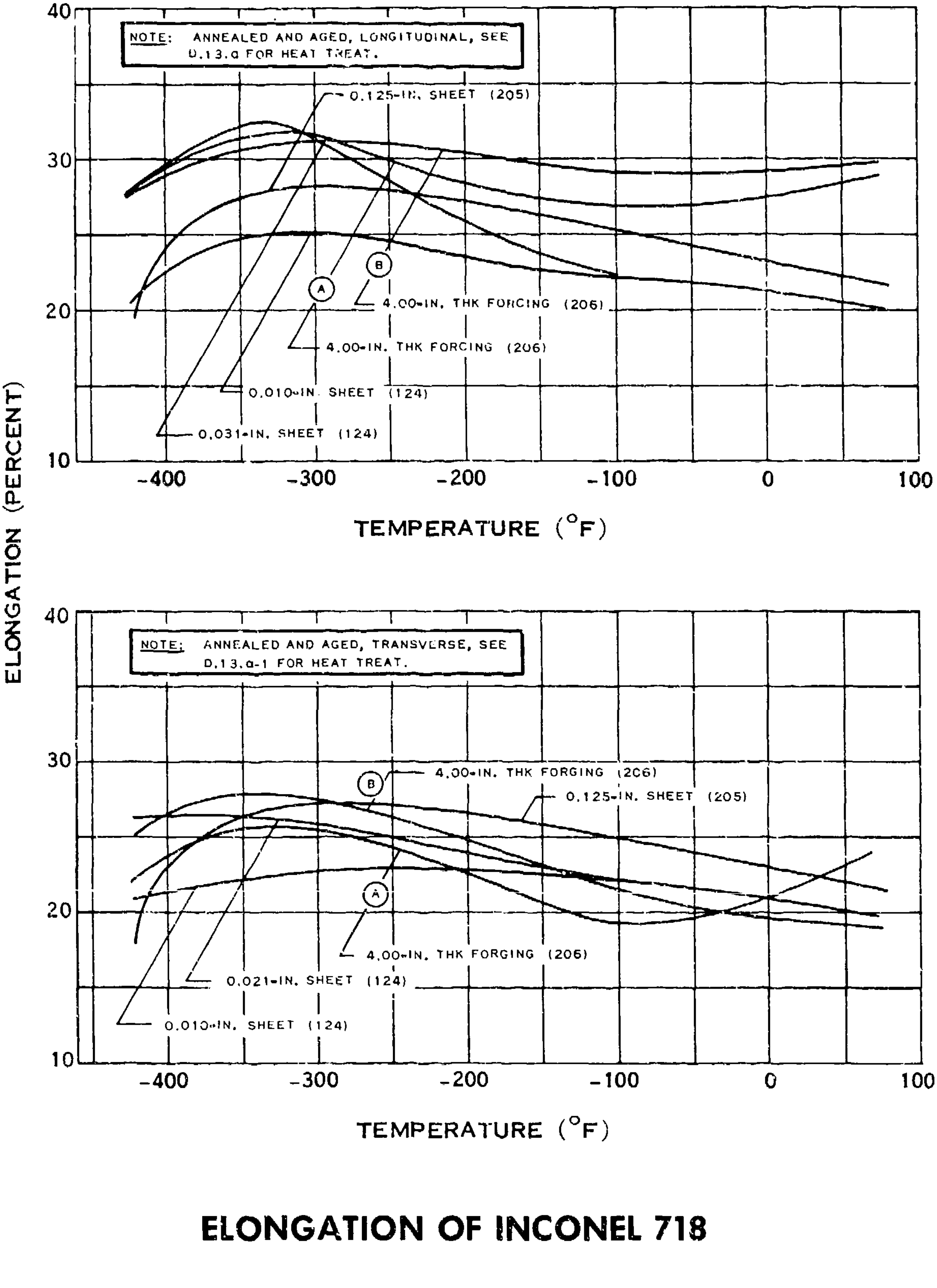
(6-68)



(6-68)

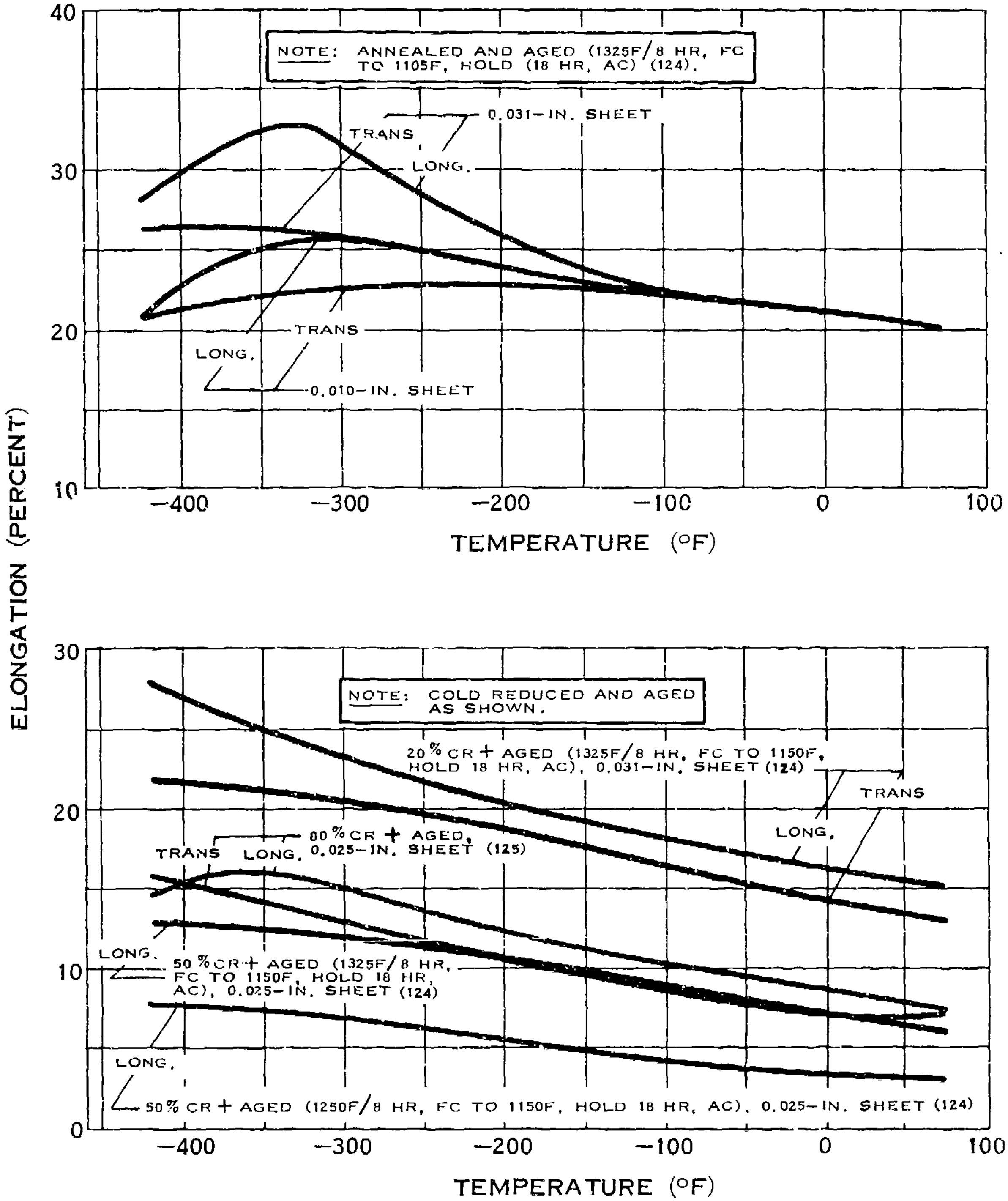
TENSILE STRENGTH OF INCONEL 718

D.13.c

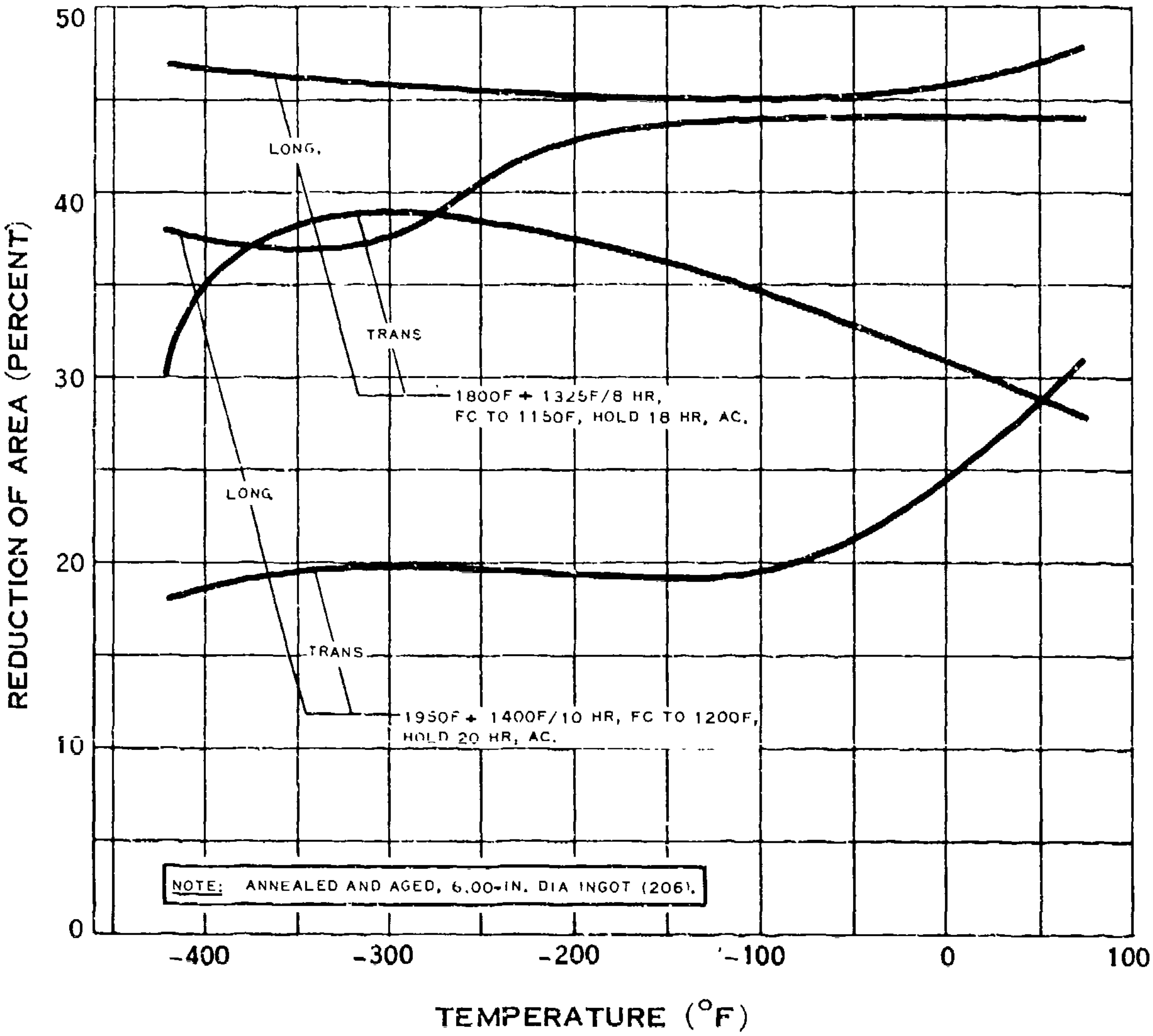


ELONGATION OF INCONEL 718

(6-68)

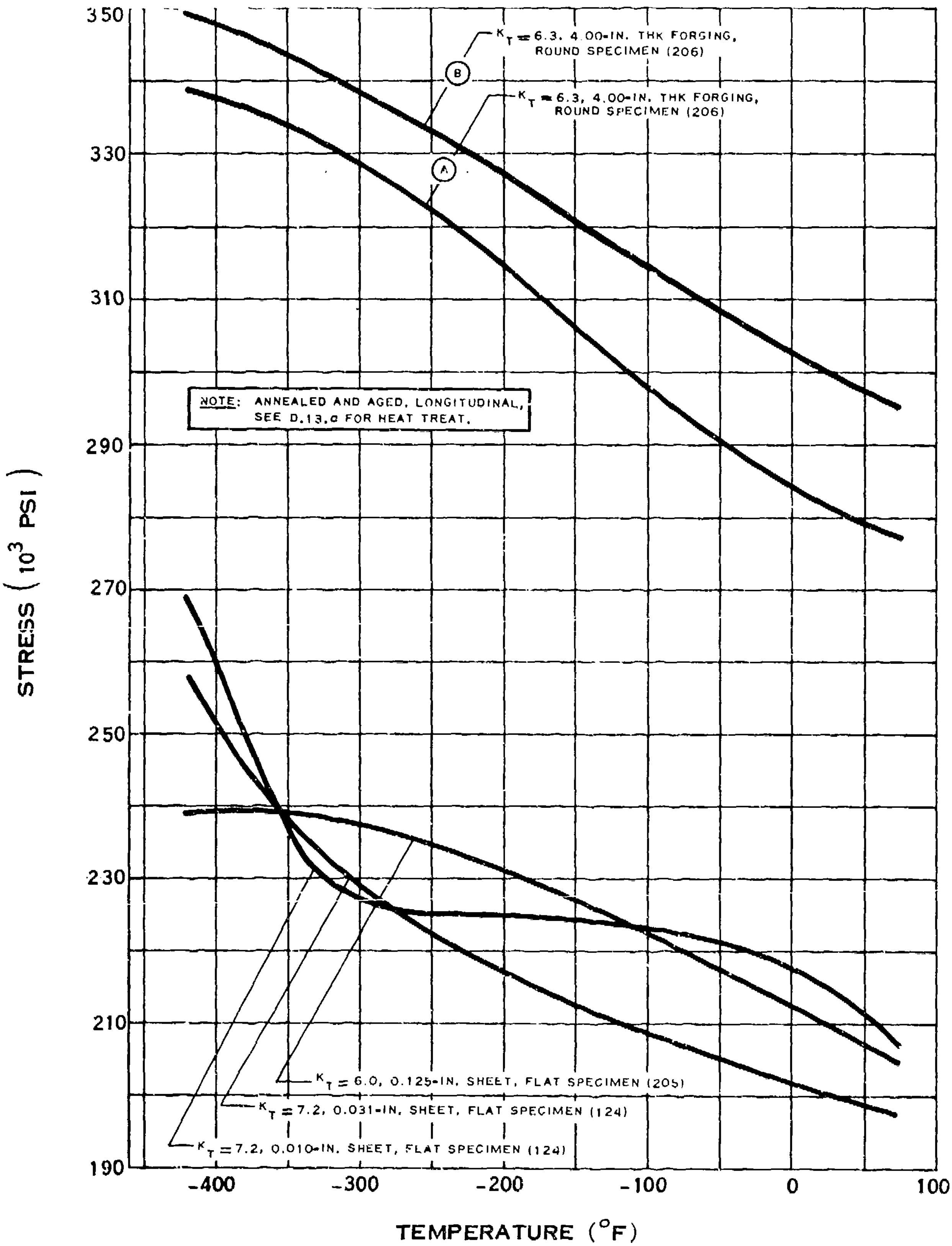


ELONGATION OF INCONEL 718



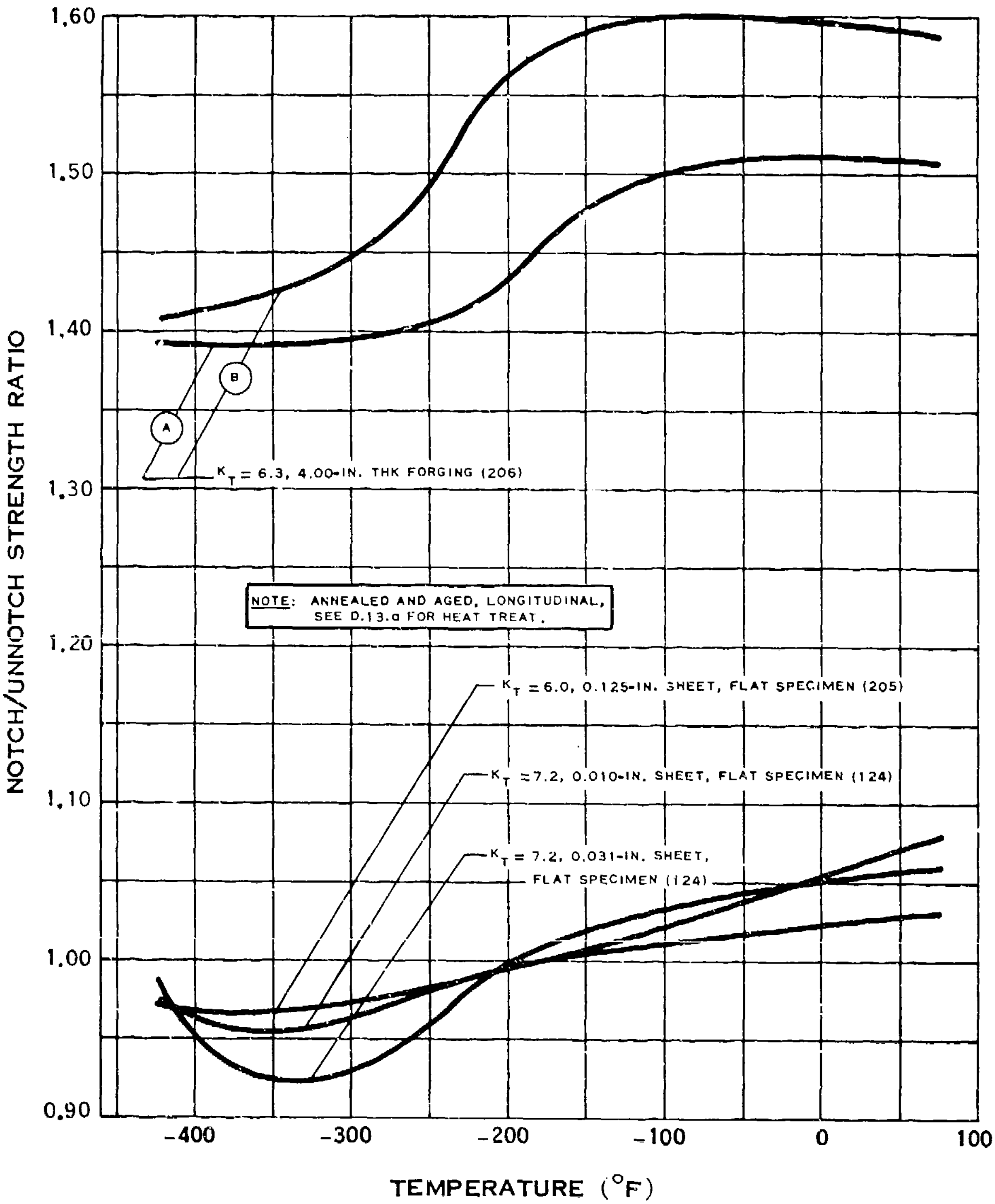
REDUCTION OF AREA OF INCONEL 718

(6-68)



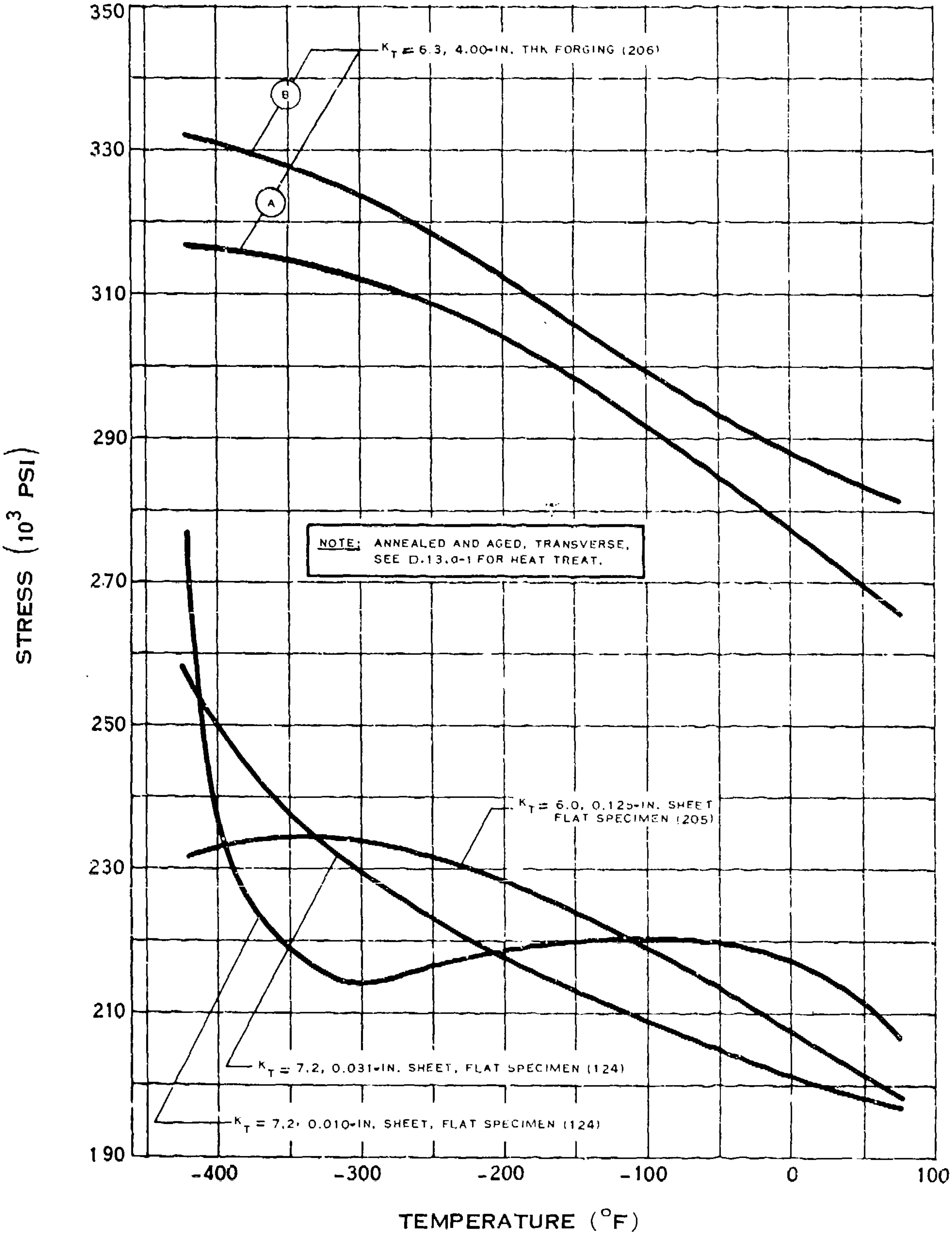
NOTCH TENSILE STRENGTH OF INCONEL 718

D.13.e-1

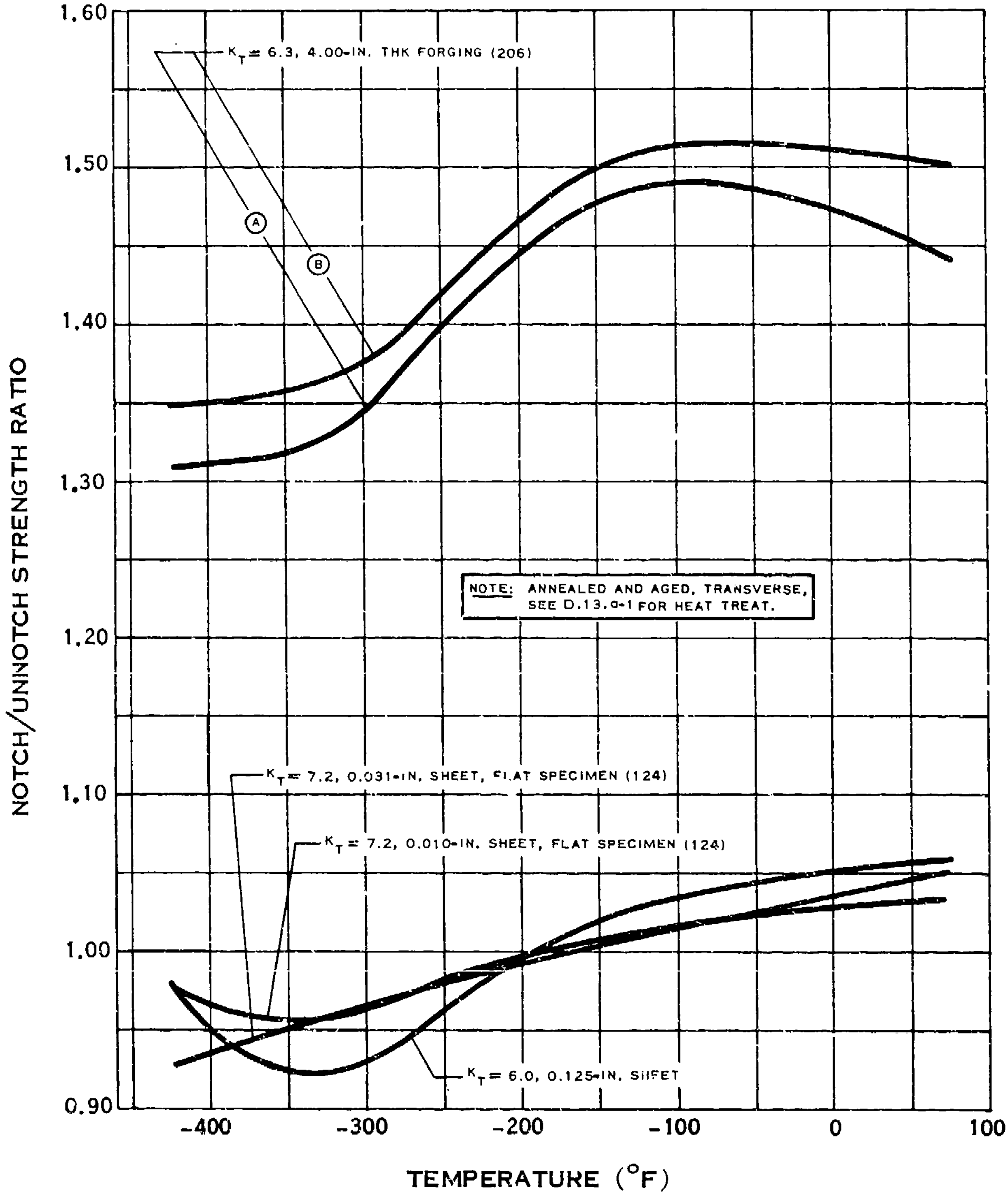


NOTCH STRENGTH RATIO OF INCONEL 718

(6-68)

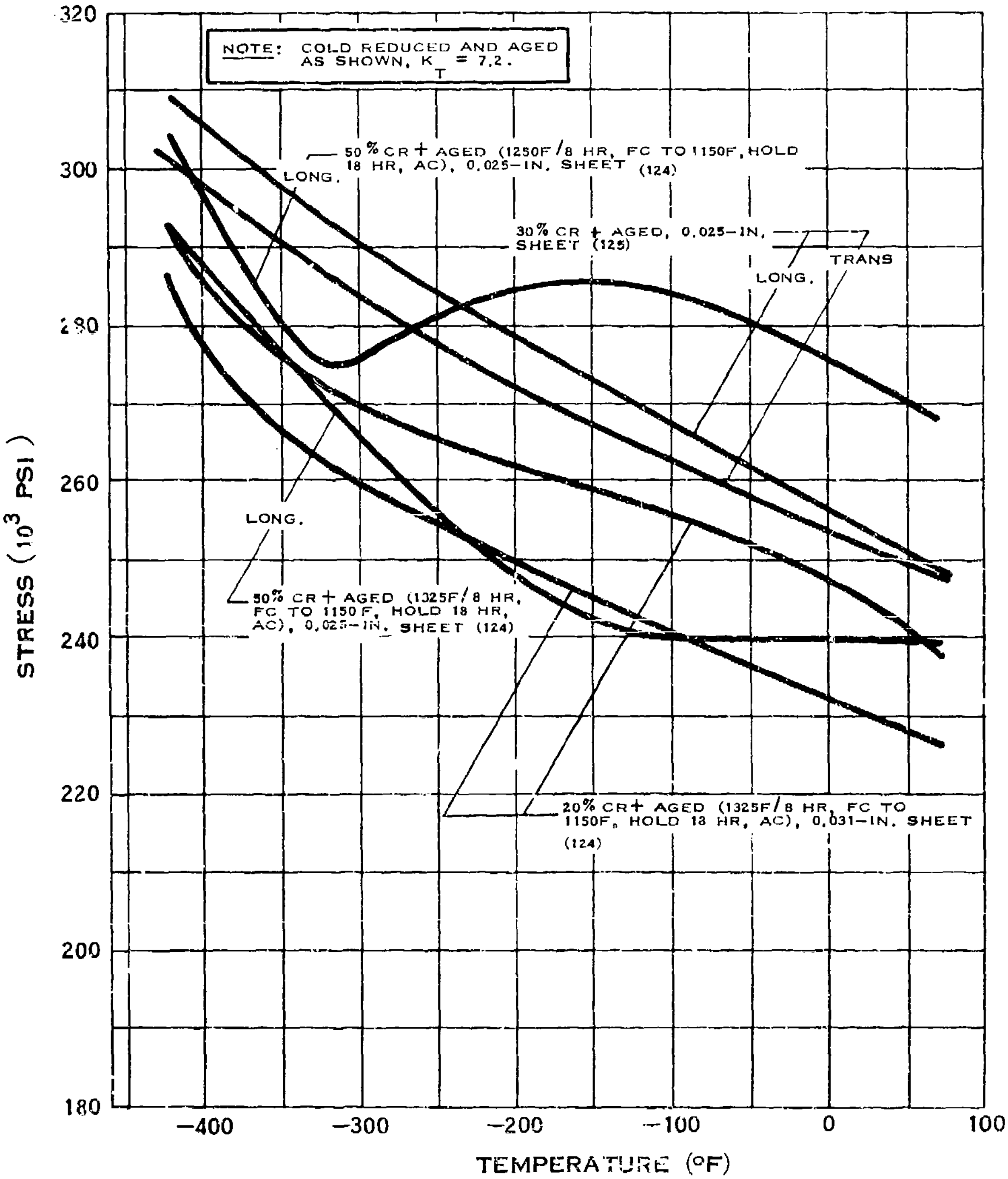


NOTCH TENSILE STRENGTH OF INCONEL 718



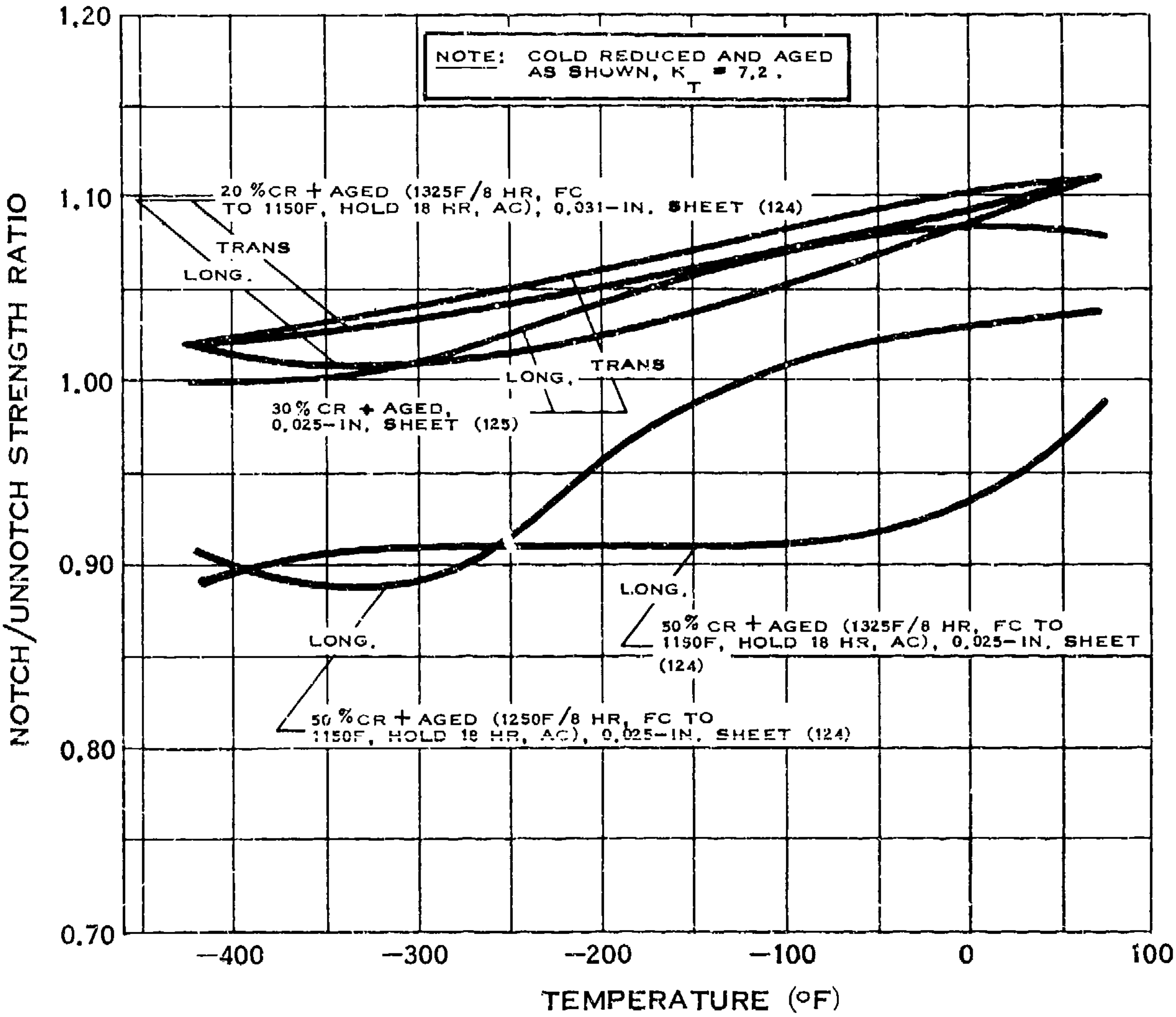
NOTCH STRENGTH RATIO OF INCONEL 718

(6-68)



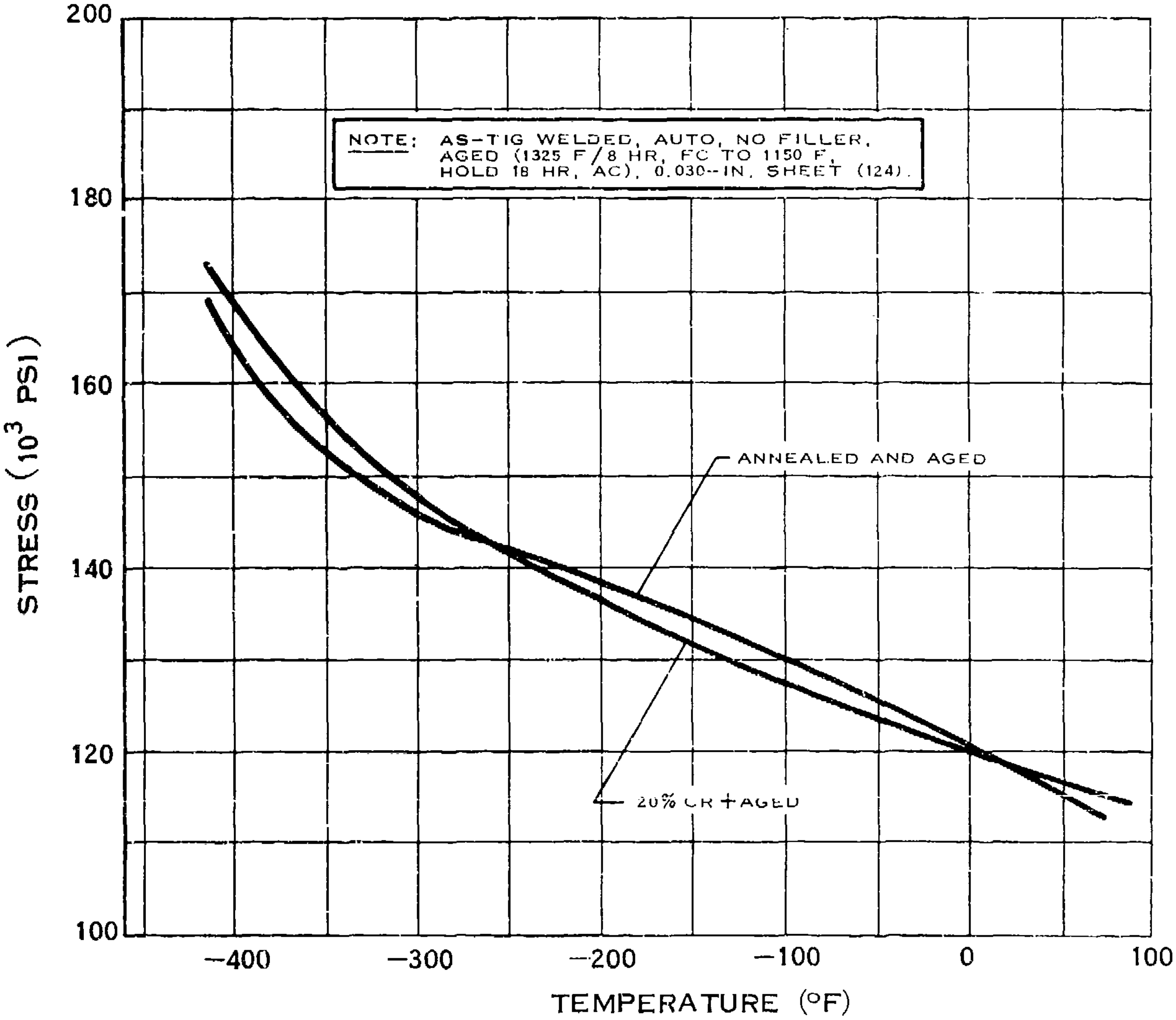
NOTCH TENSILE STRENGTH OF INCONEL 718

(6-68)



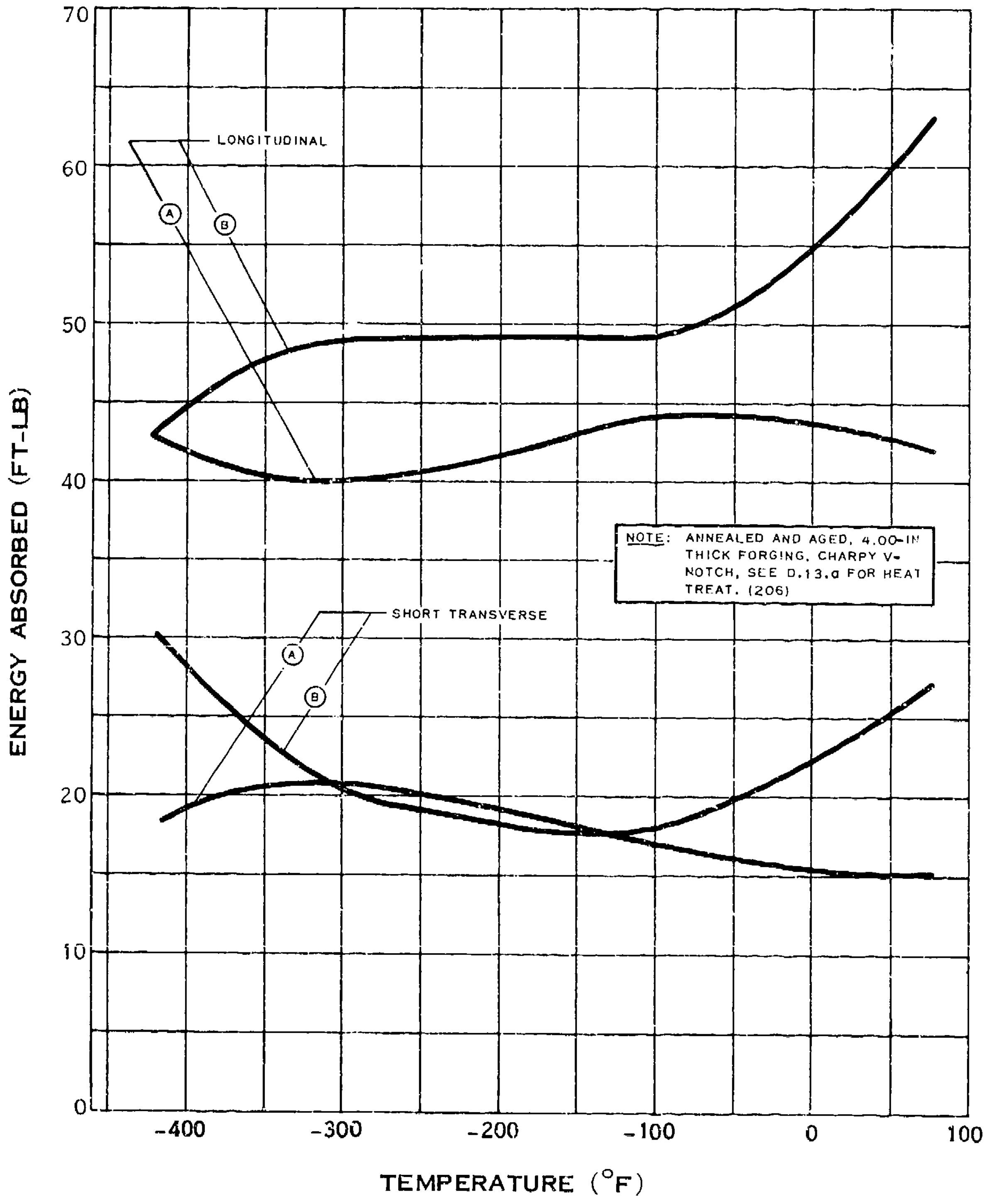
NOTCH STRENGTH RATIO OF INCONEL 718

(6-68)



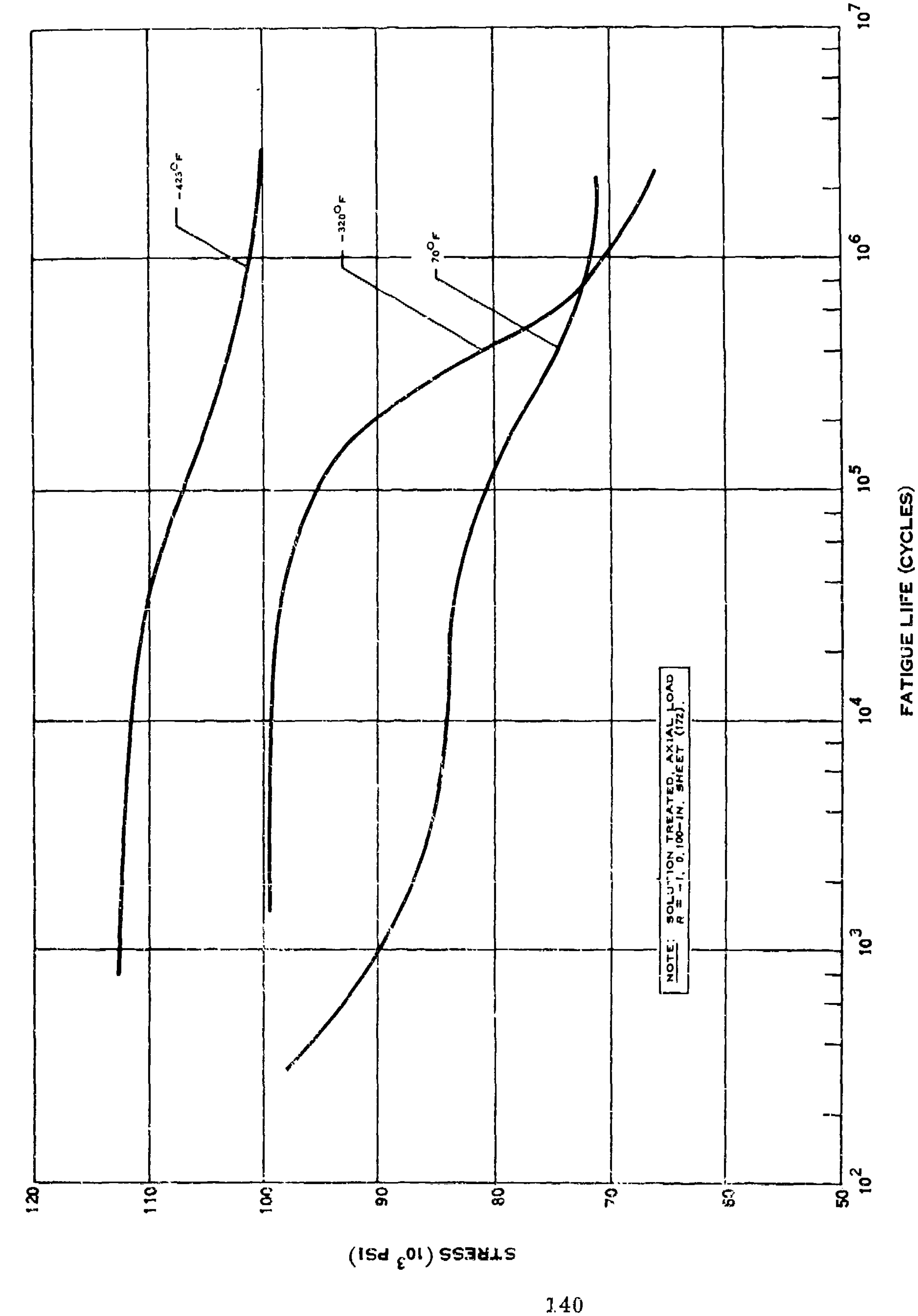
WELD TENSILE STRENGTH OF INCONEL 718

(1-65)

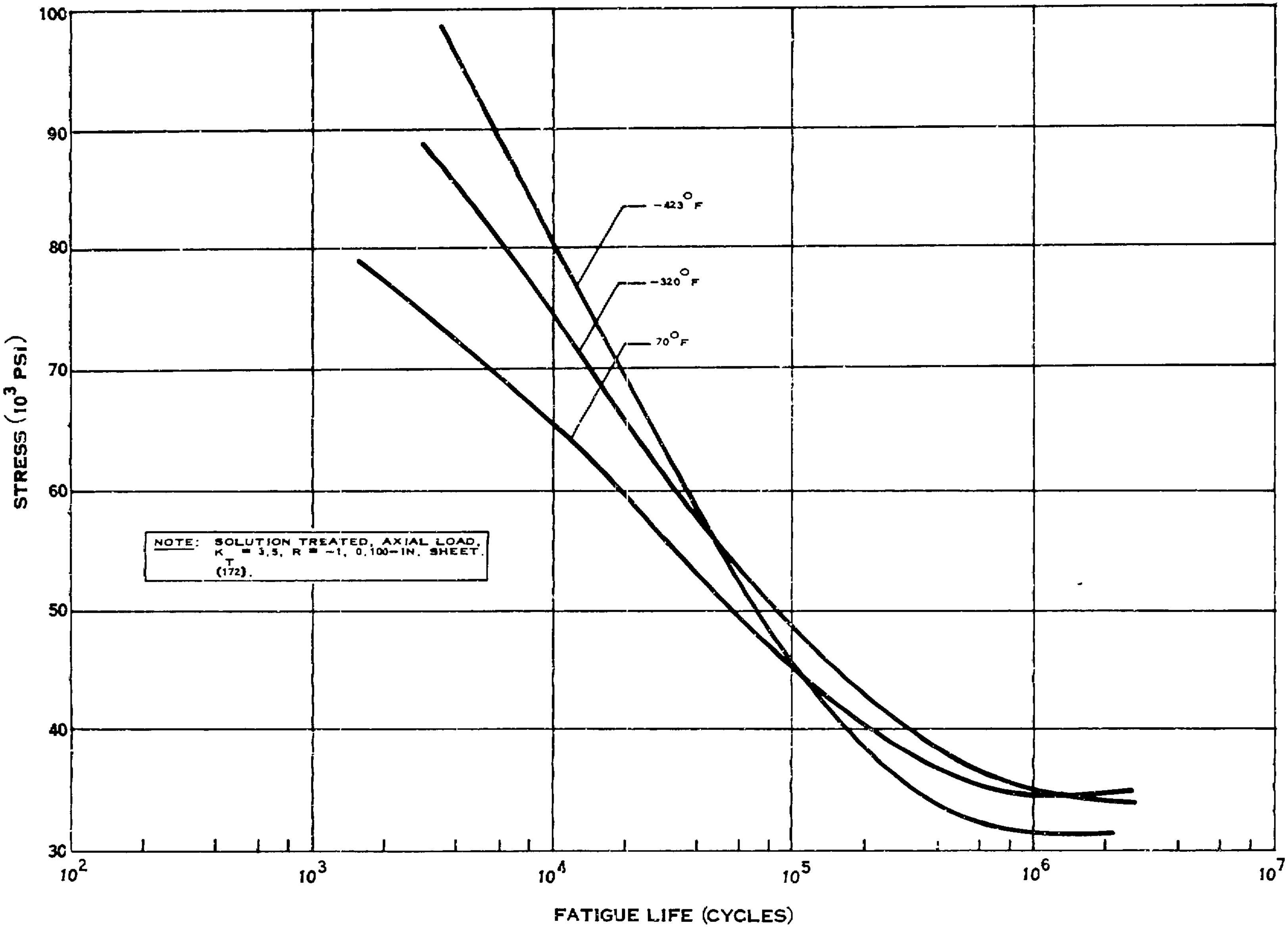


IMPACT STRENGTH OF INCONEL 718

(6-68)

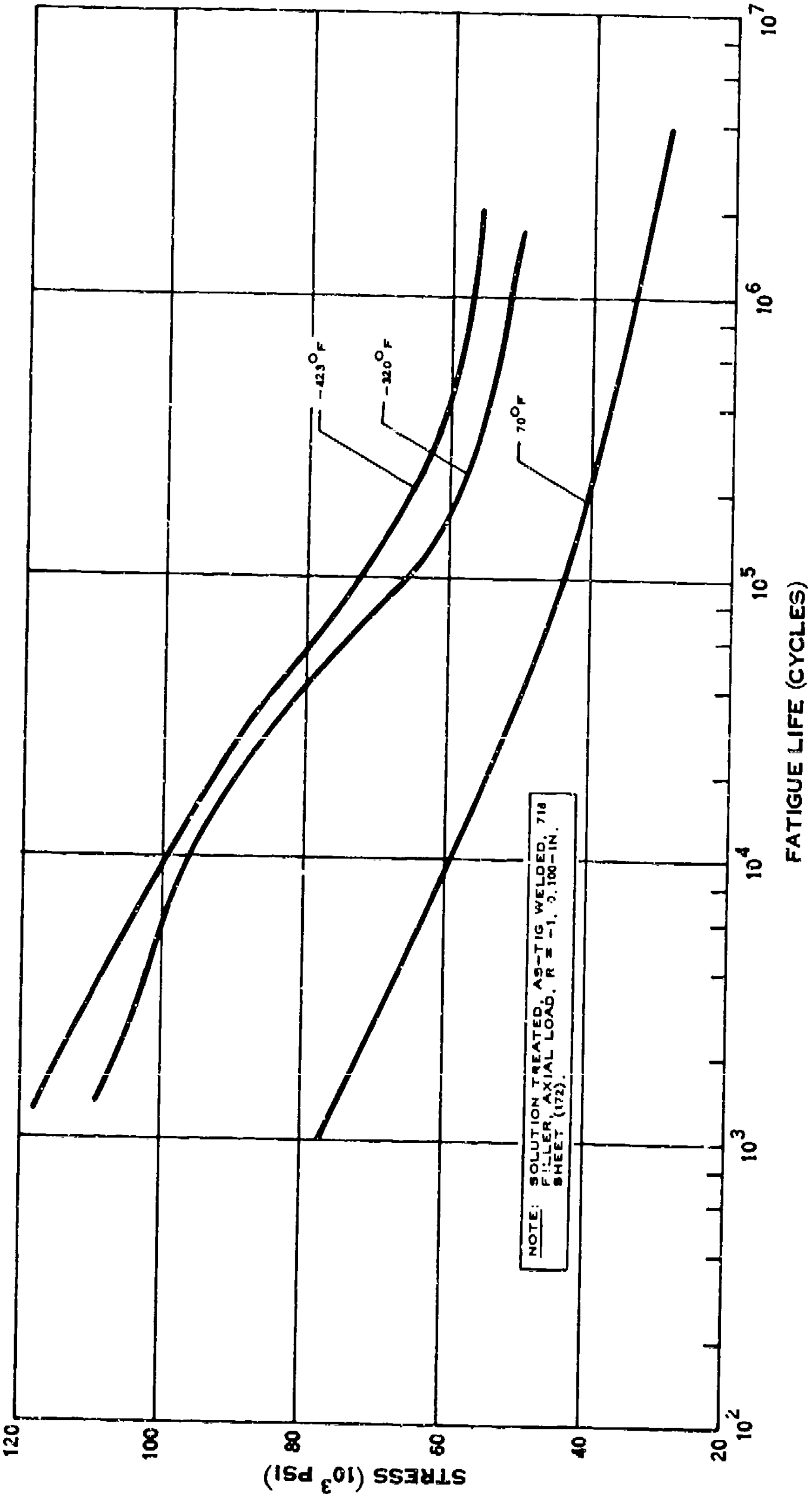


FATIGUE STRENGTH OF INCONEL 718

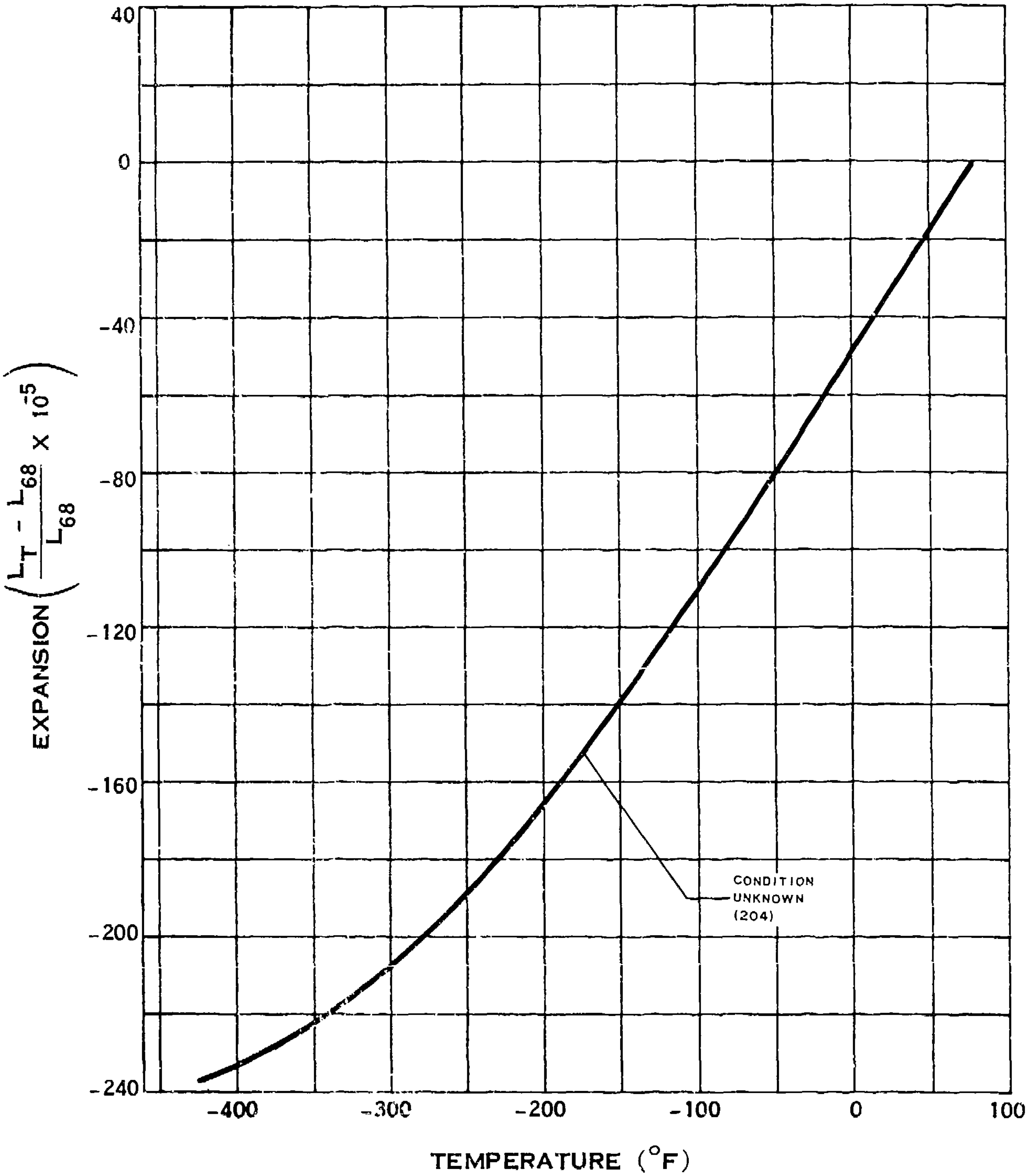


NOTCH FATIGUE STRENGTH OF INCONEL 718

(3—66)

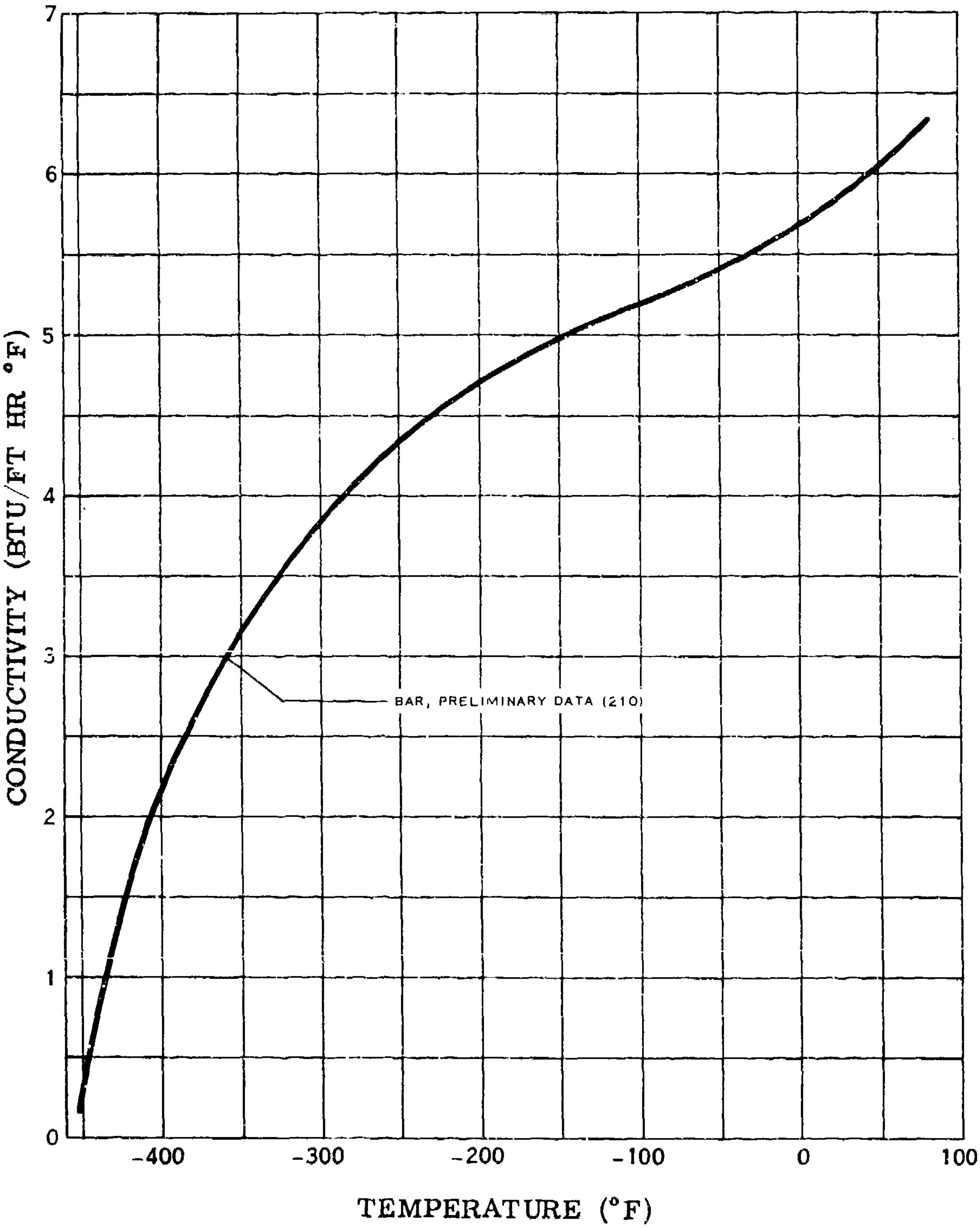


WELD FATIGUE STRENGTH OF INCONEL 718



THERMAL EXPANSION OF INCONEL 718

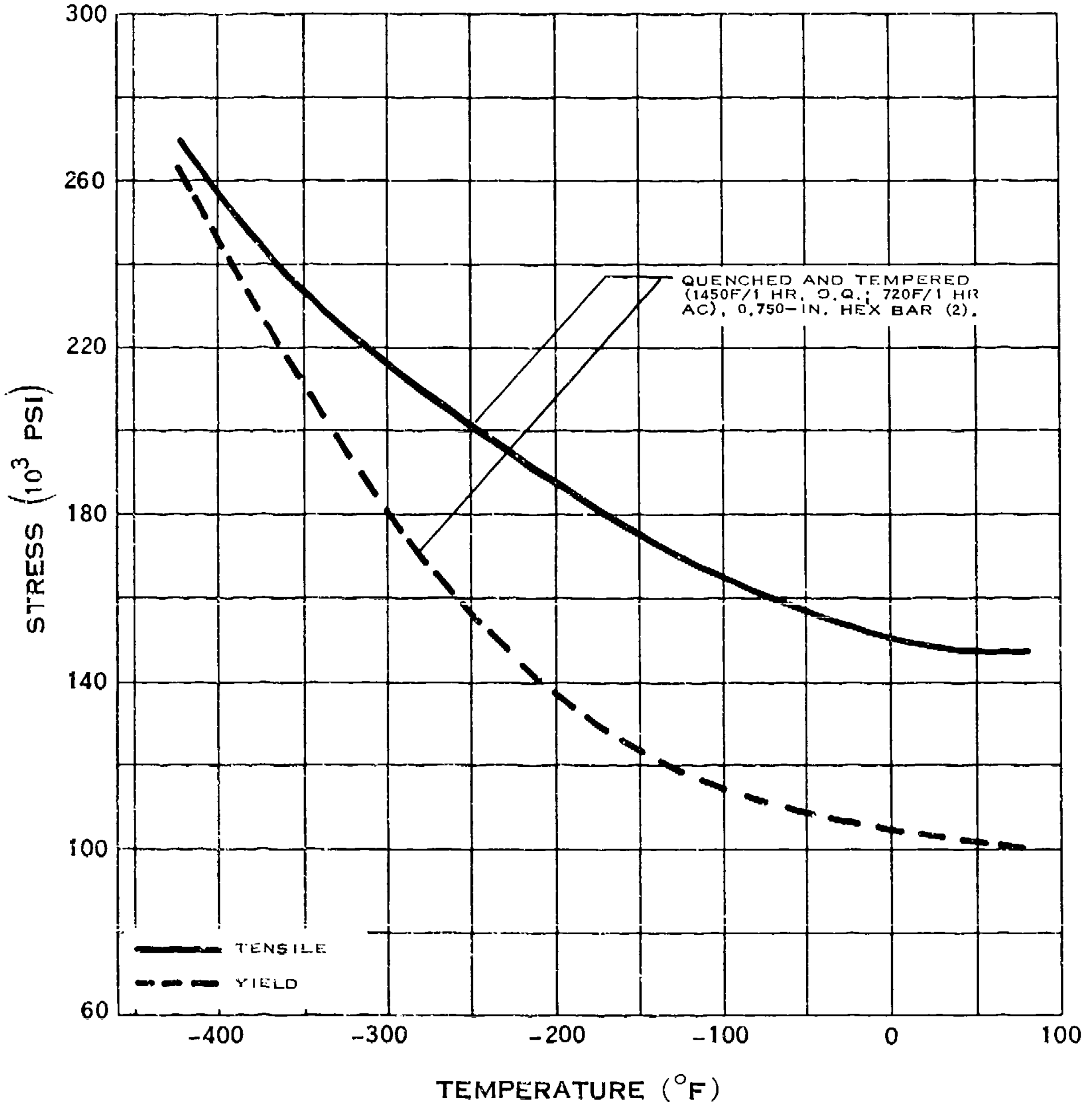
(6-68)



THERMAL CONDUCTIVITY OF INCONEL 718

E - ALLOY STEELS

E.1.ab



STRENGTH OF 1075 STEEL

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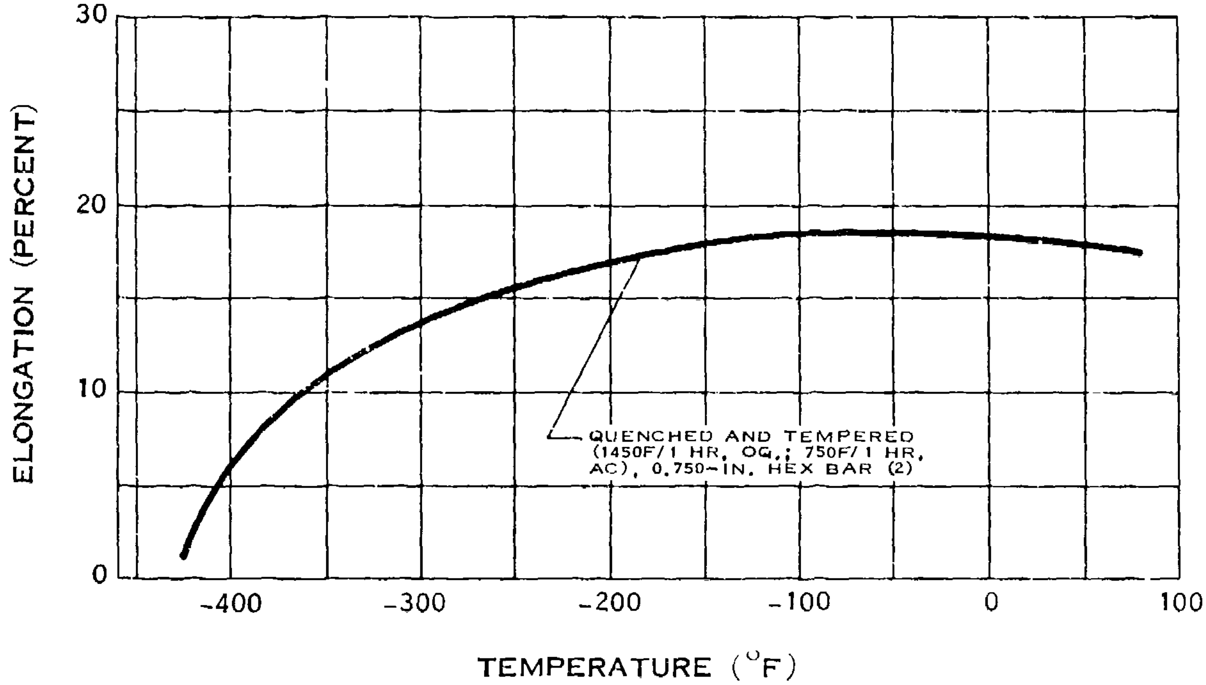
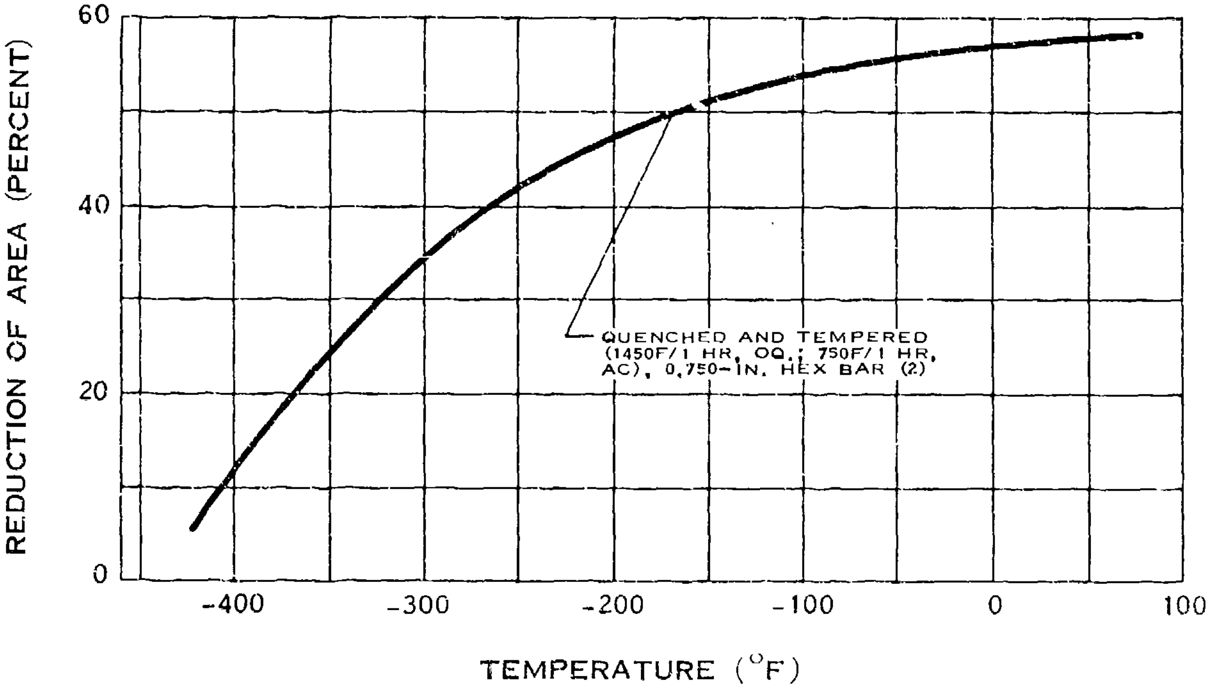
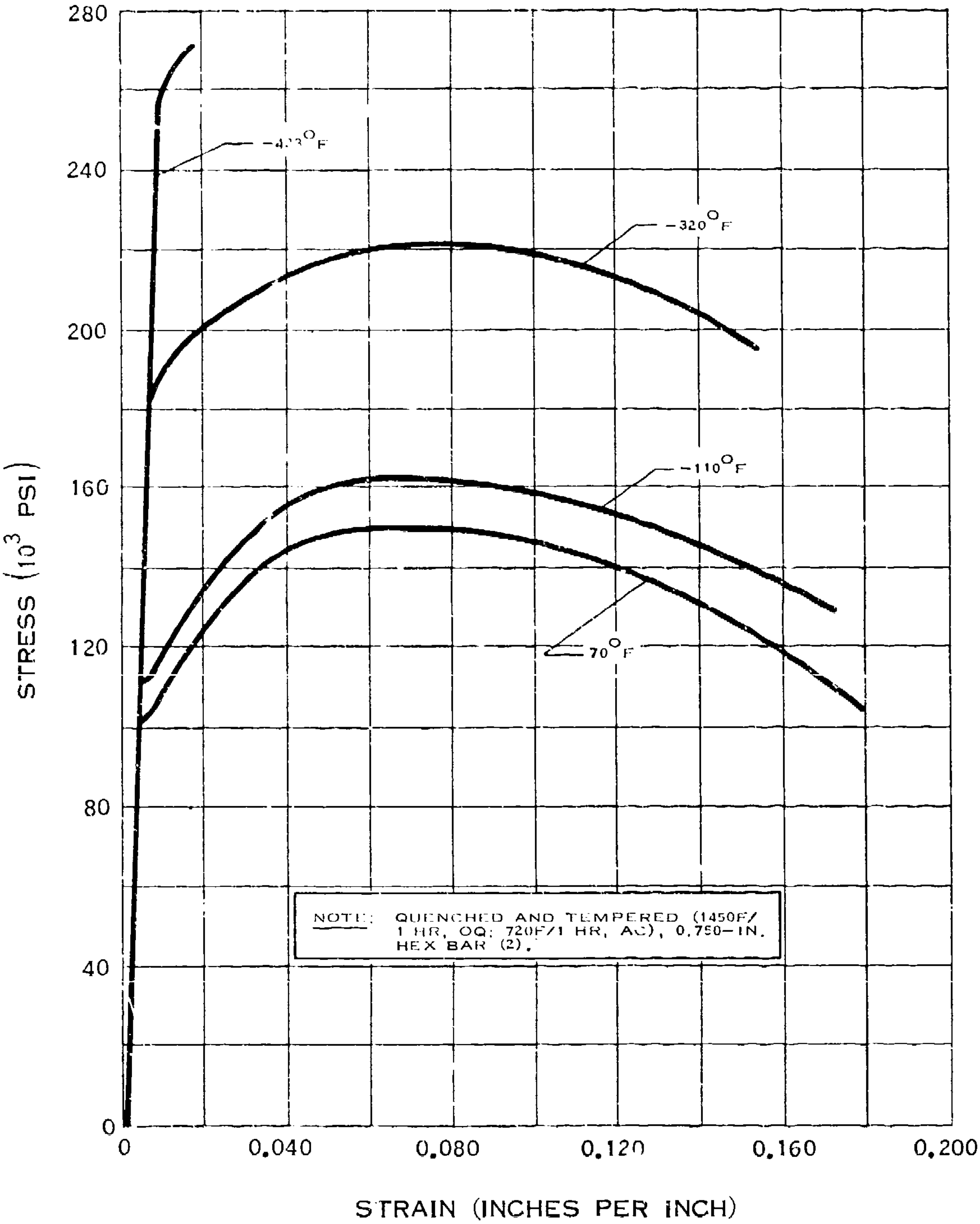


ELONGATION OF 1075 STEEL

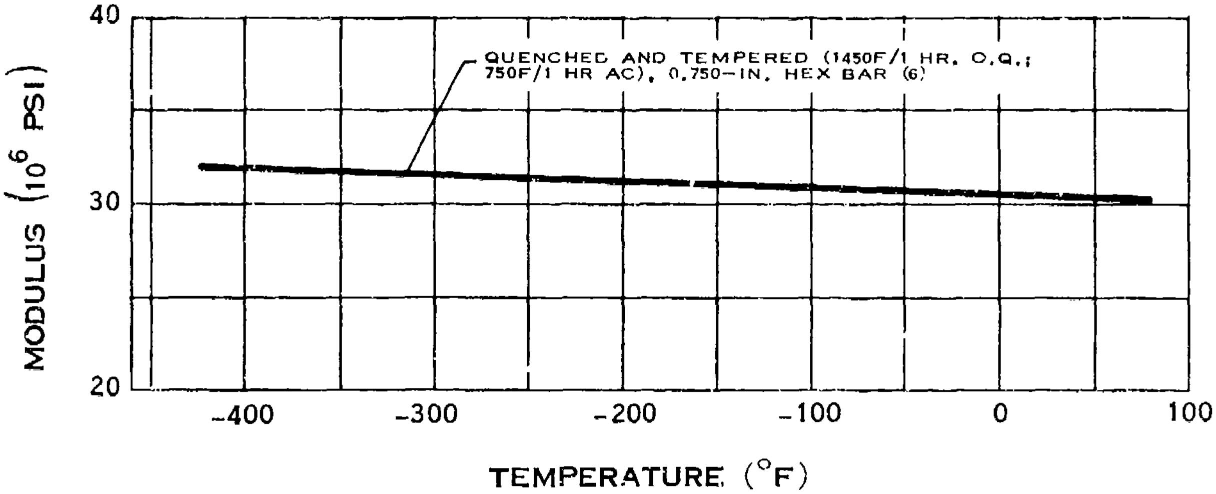


REDUCTION OF AREA OF 1075 STEEL

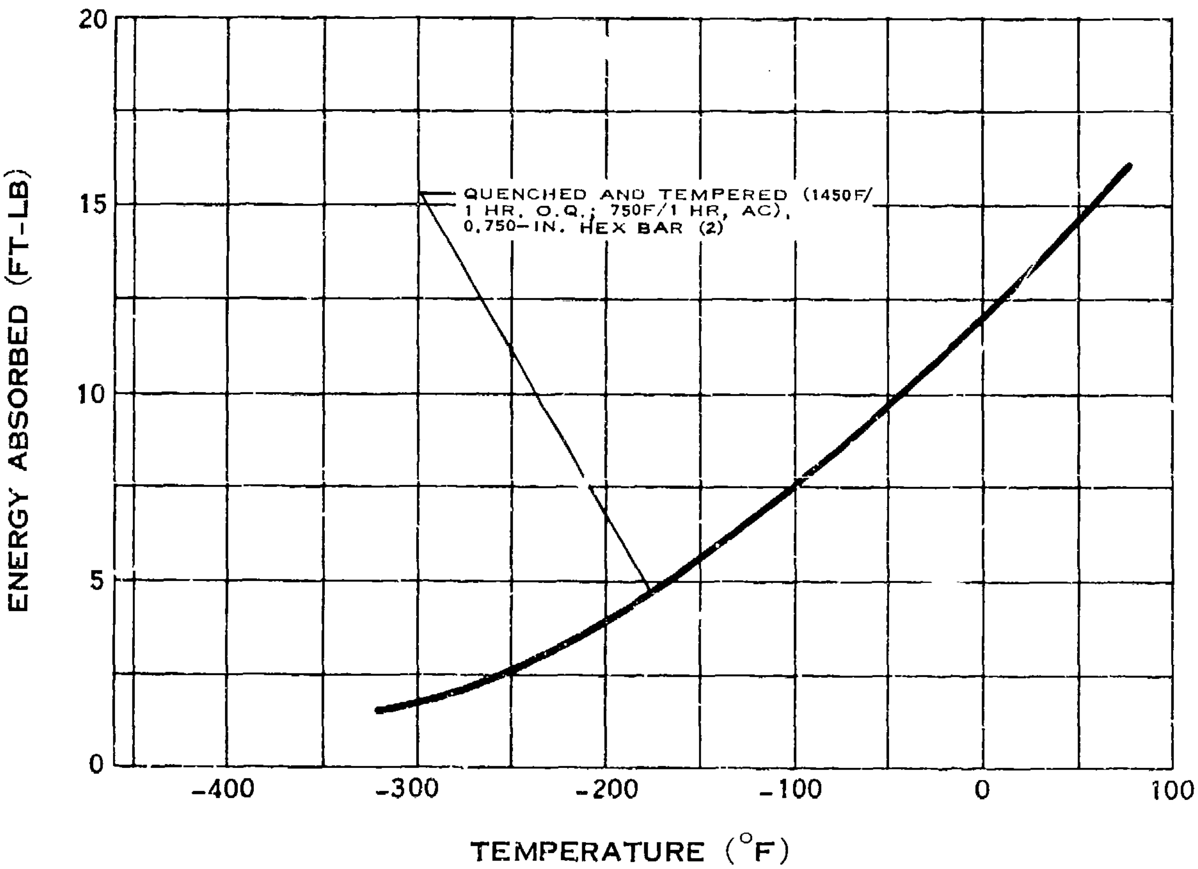
E.1.h



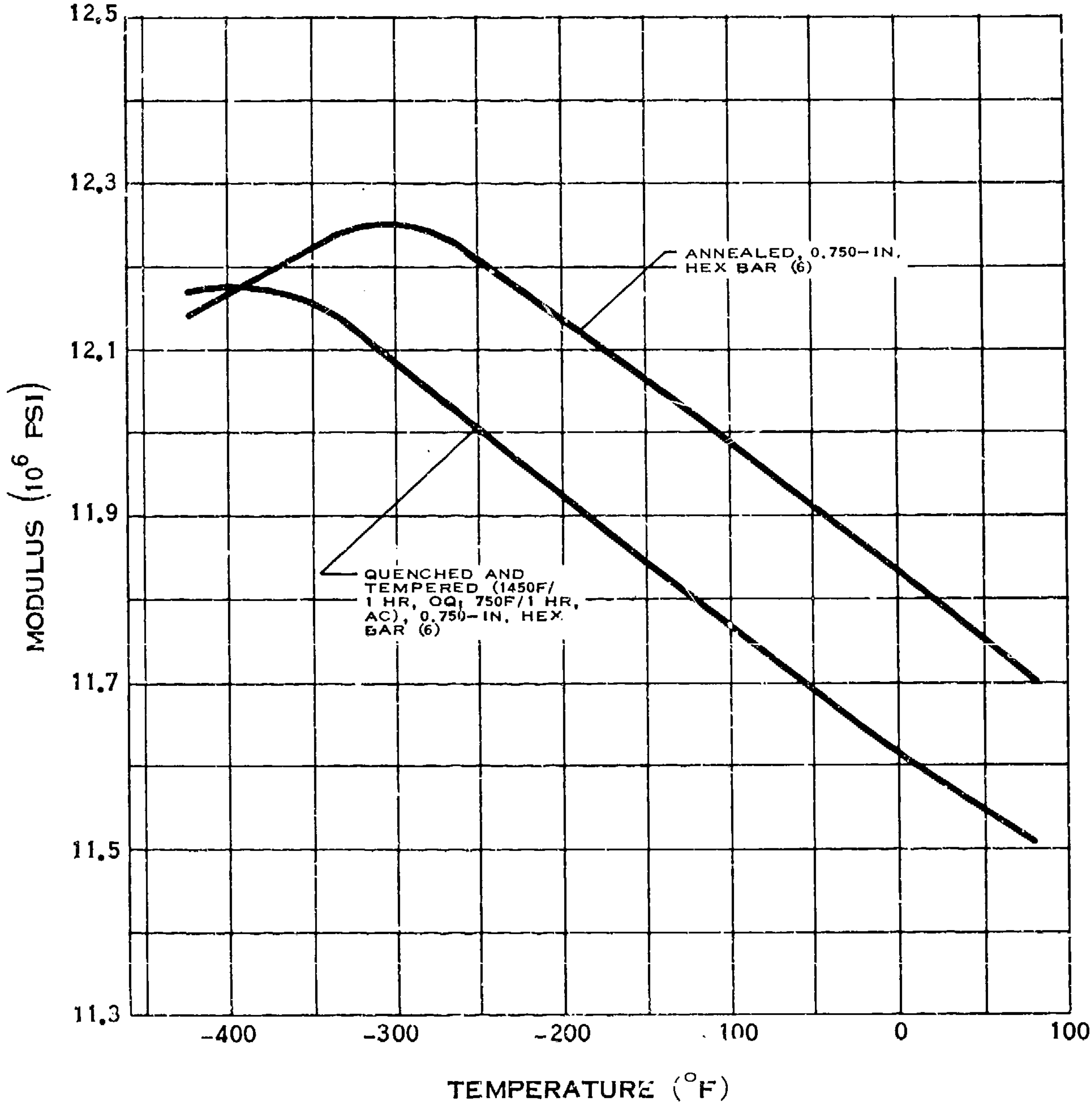
STRESS-STRAIN DIAGRAM FOR 1075 STEEL



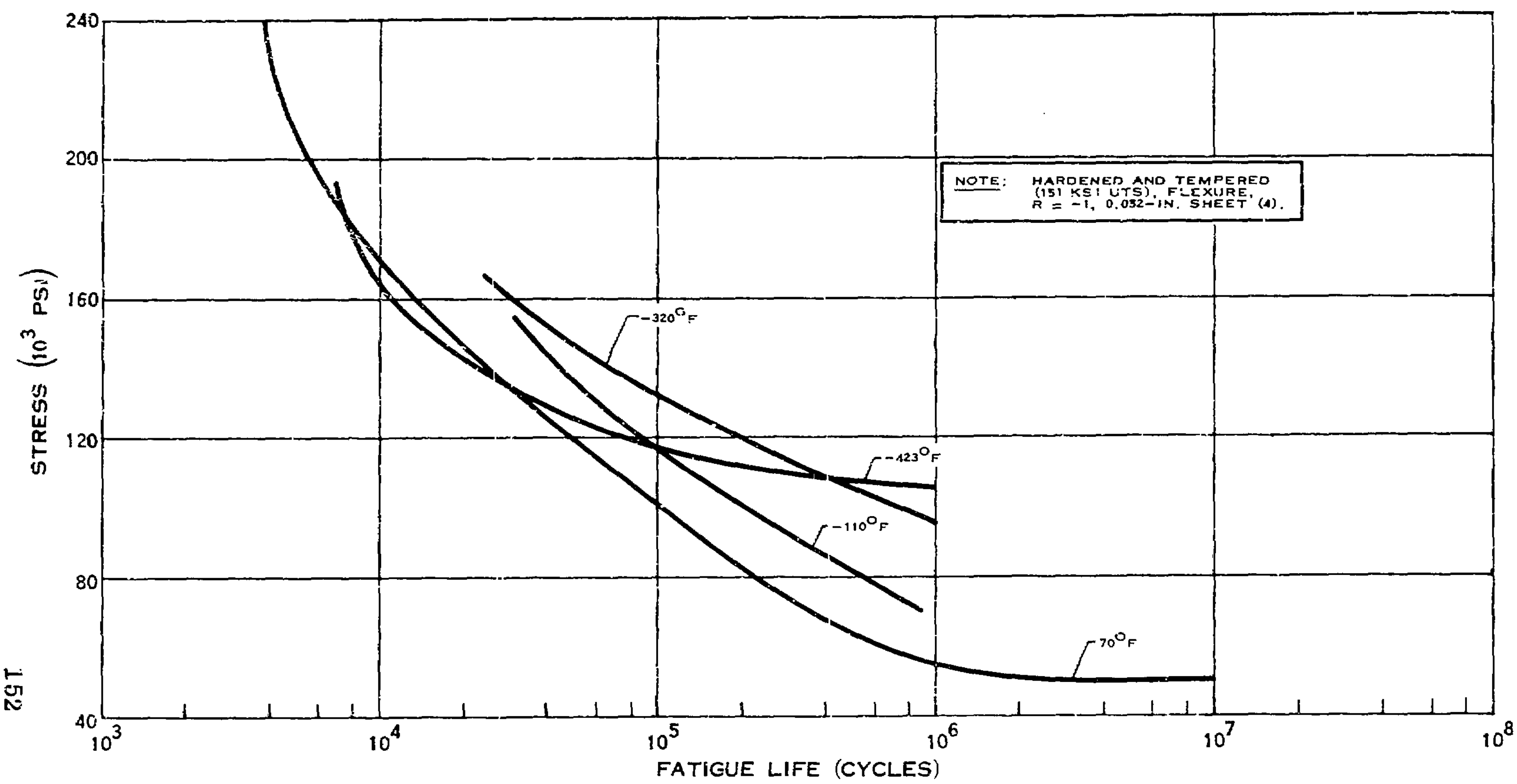
MODULUS OF ELASTICITY OF 1075 STEEL



IMPACT STRENGTH OF 1075 STEEL

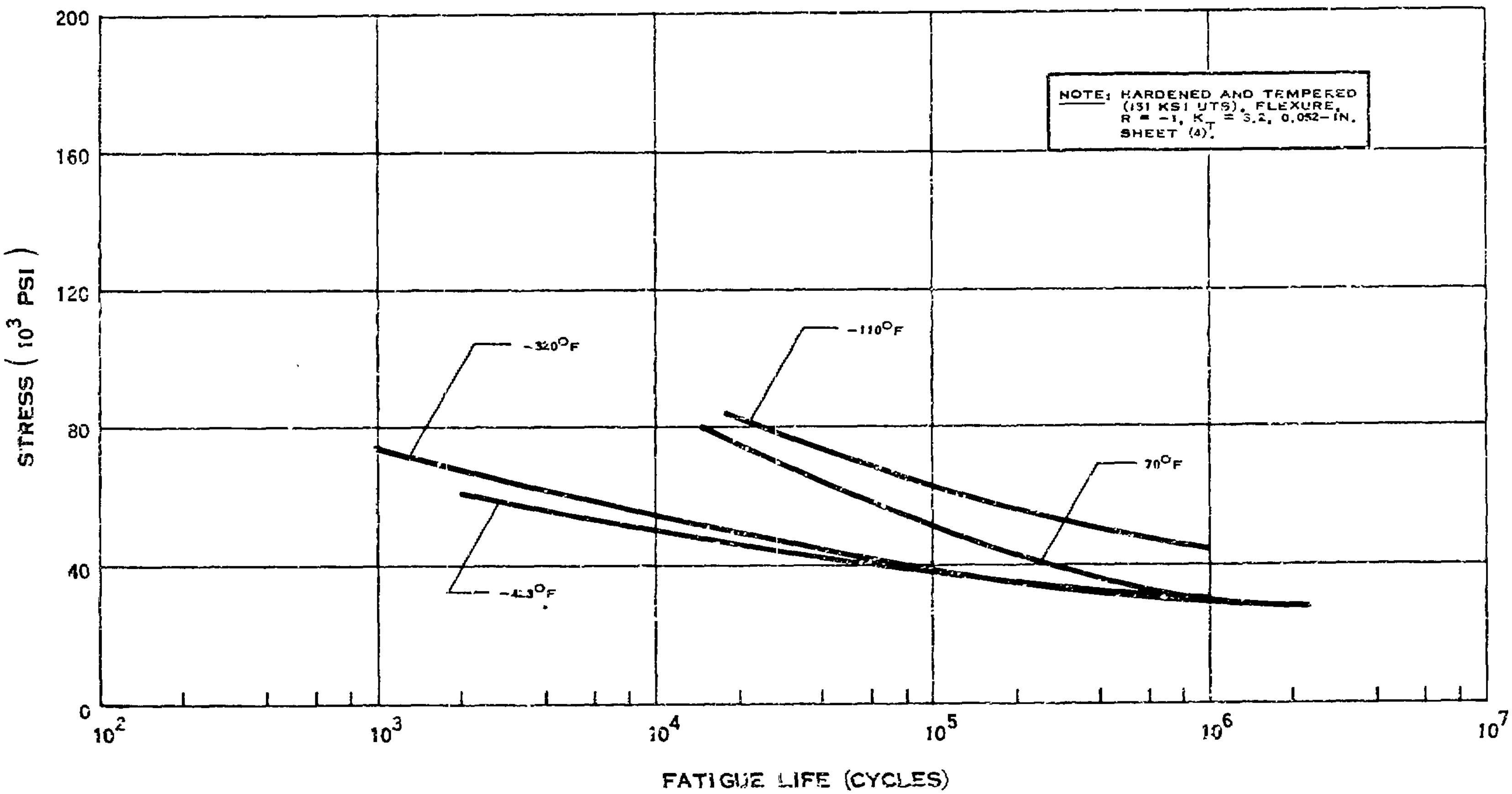


MODULUS OF RIGIDITY OF 1075 STEEL



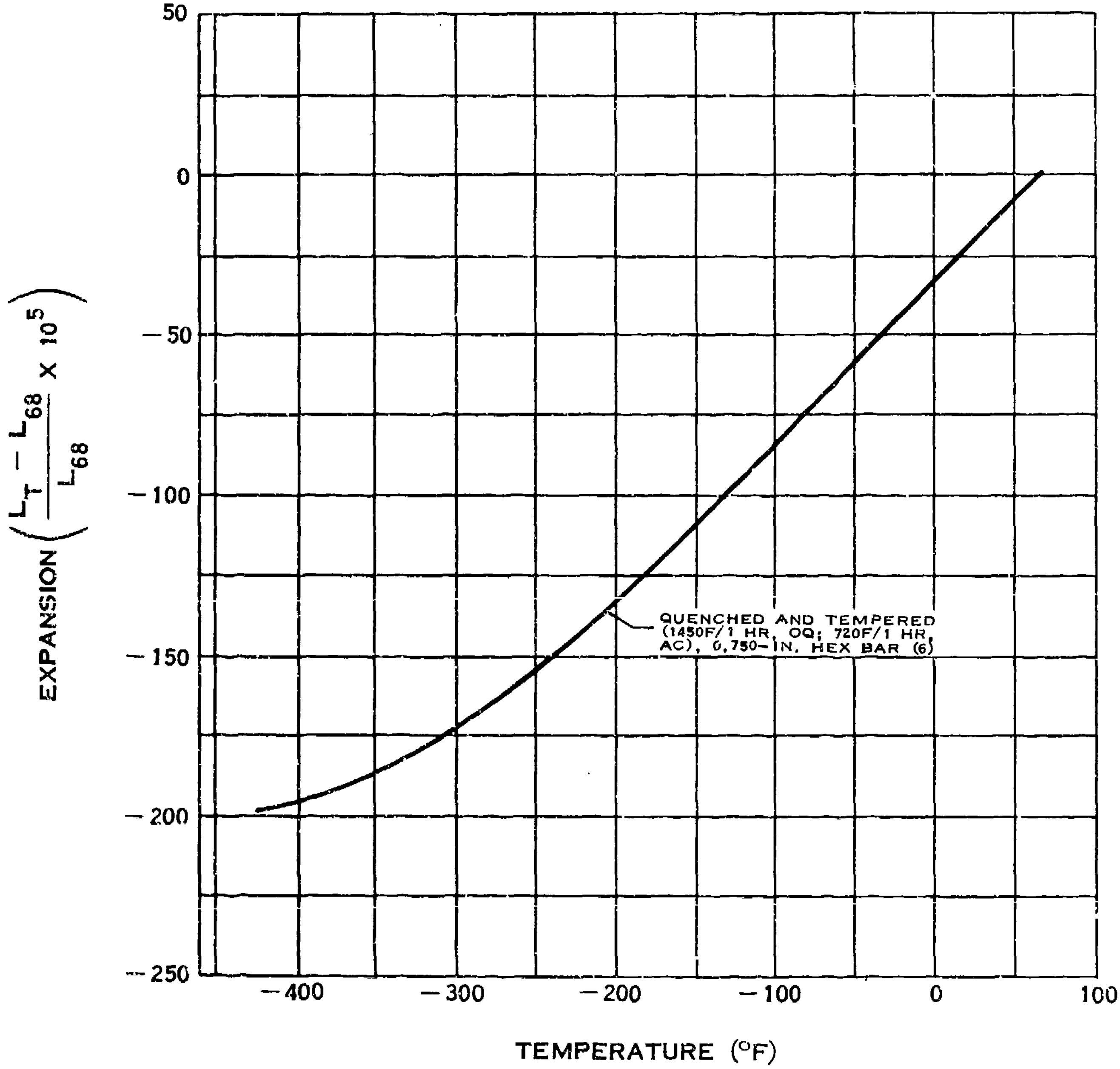
FATIGUE STRENGTH OF 1075 STEEL

(7-64)

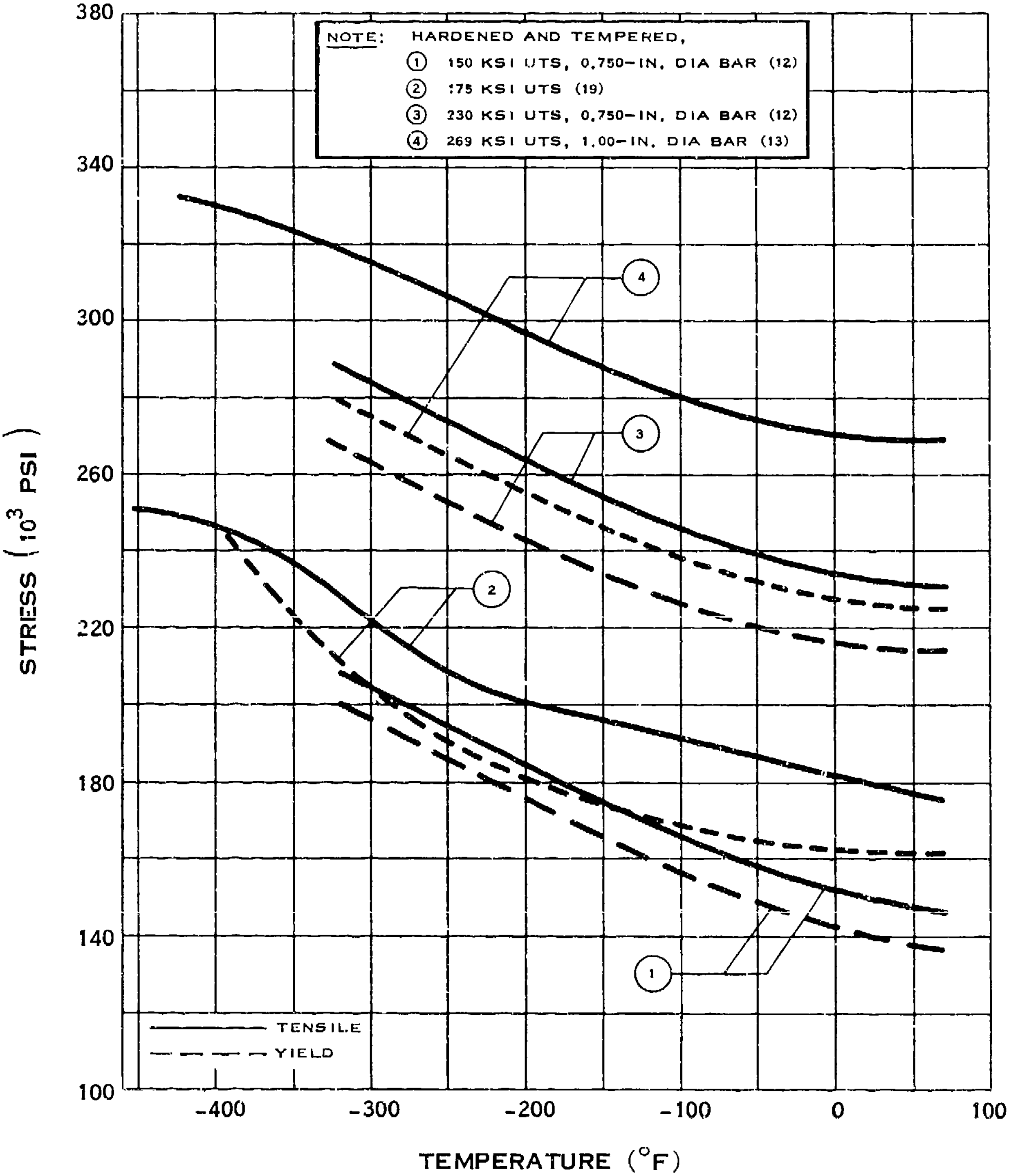


NOTCH FATIGUE STRENGTH OF 1075 STEEL

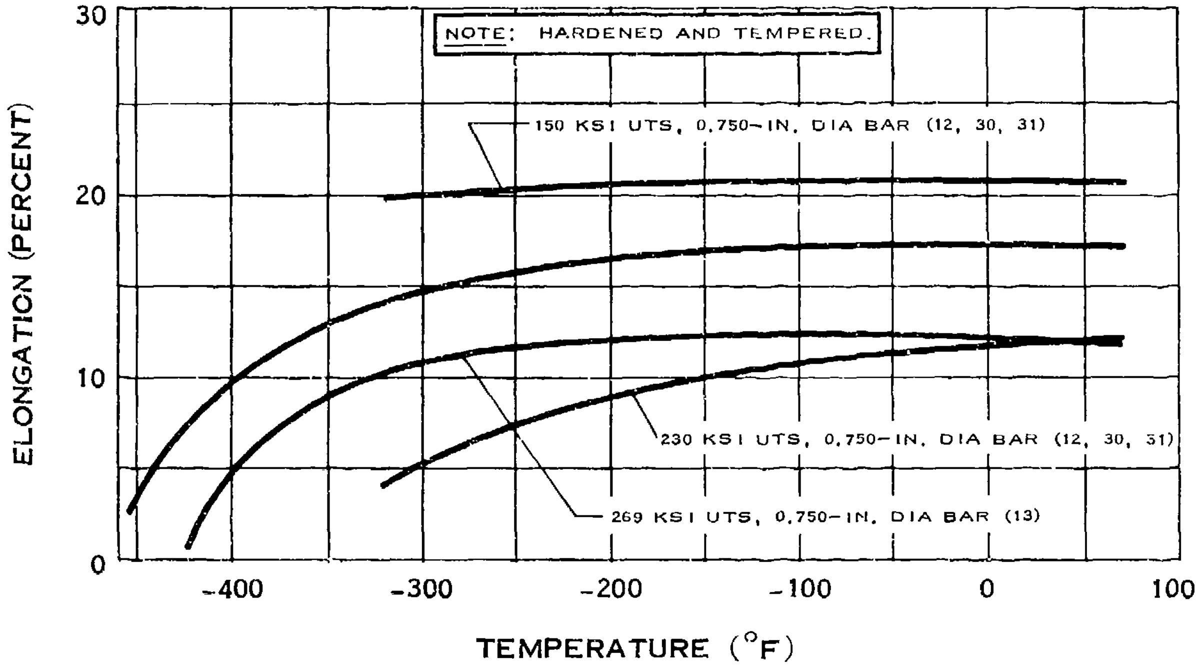
(7-64)



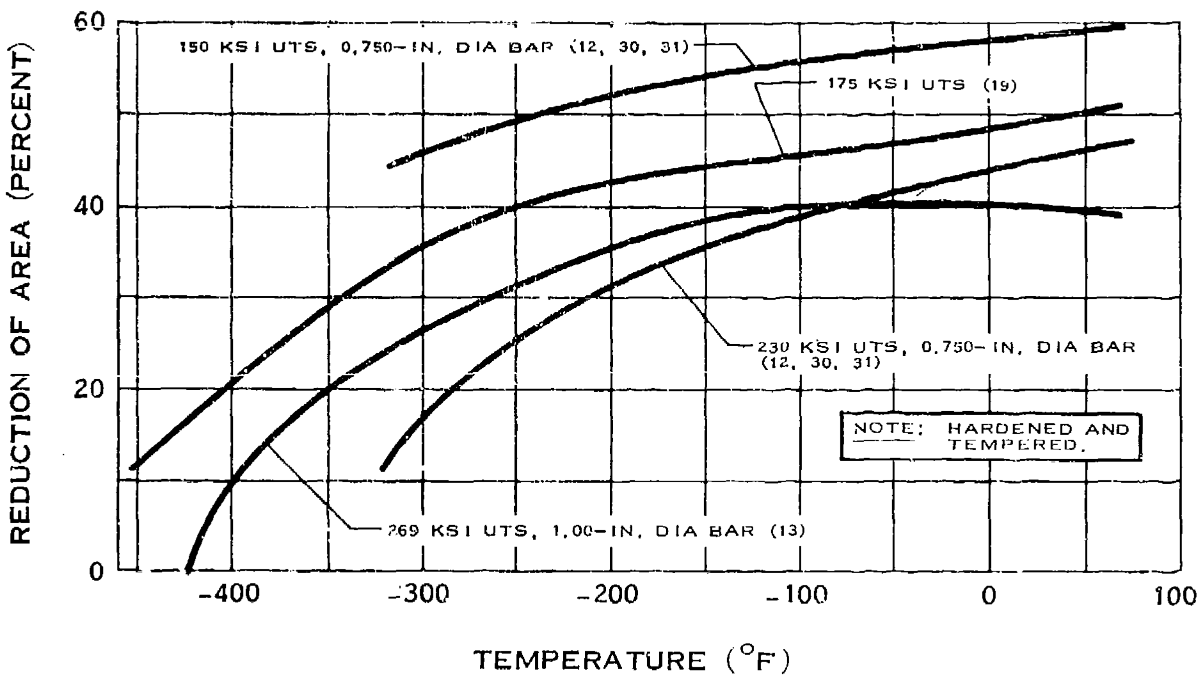
THERMAL EXPANSION OF 1075 STEEL



STRENGTH OF 4340 STEEL

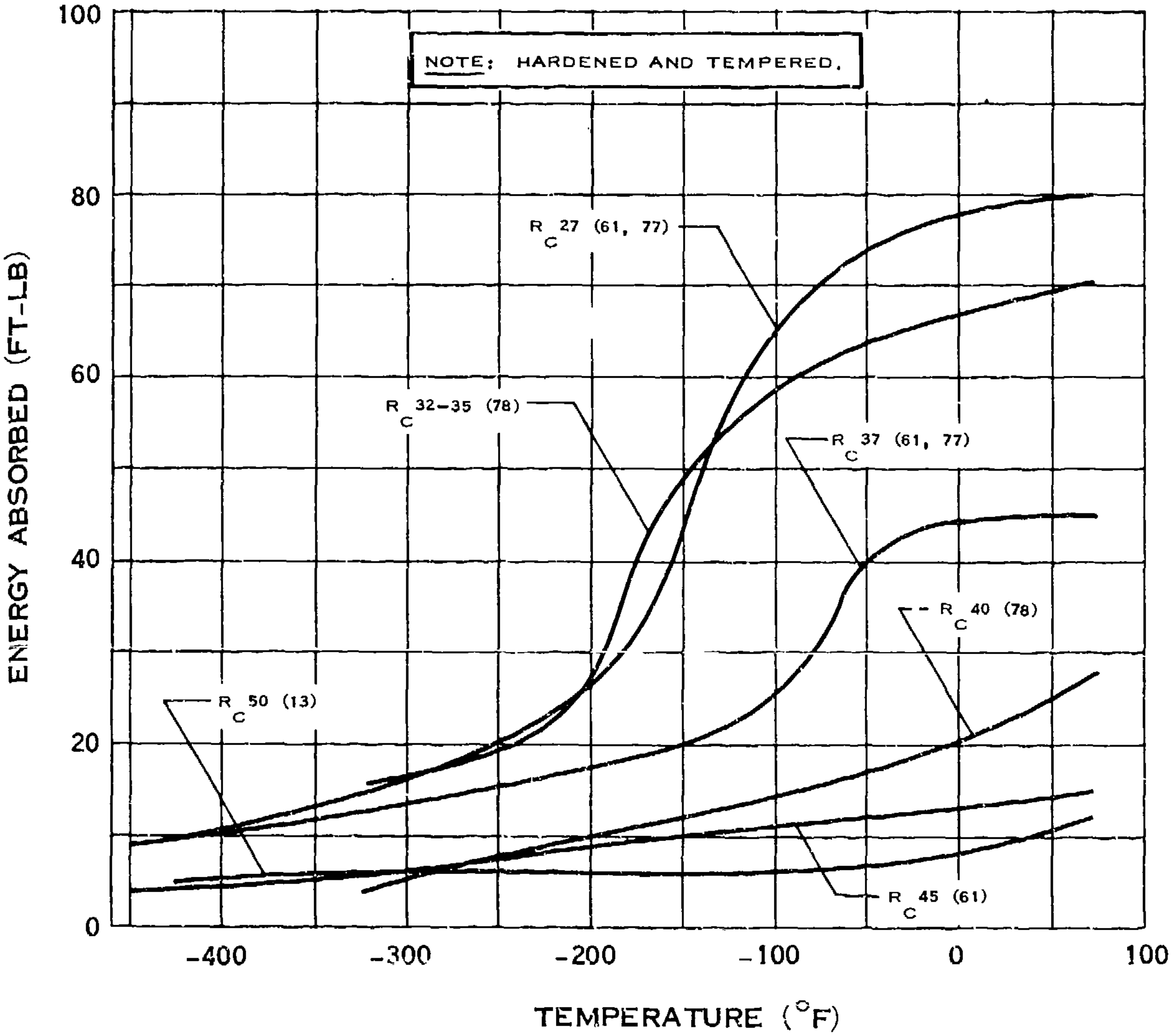


ELONGATION OF 4340 STEEL



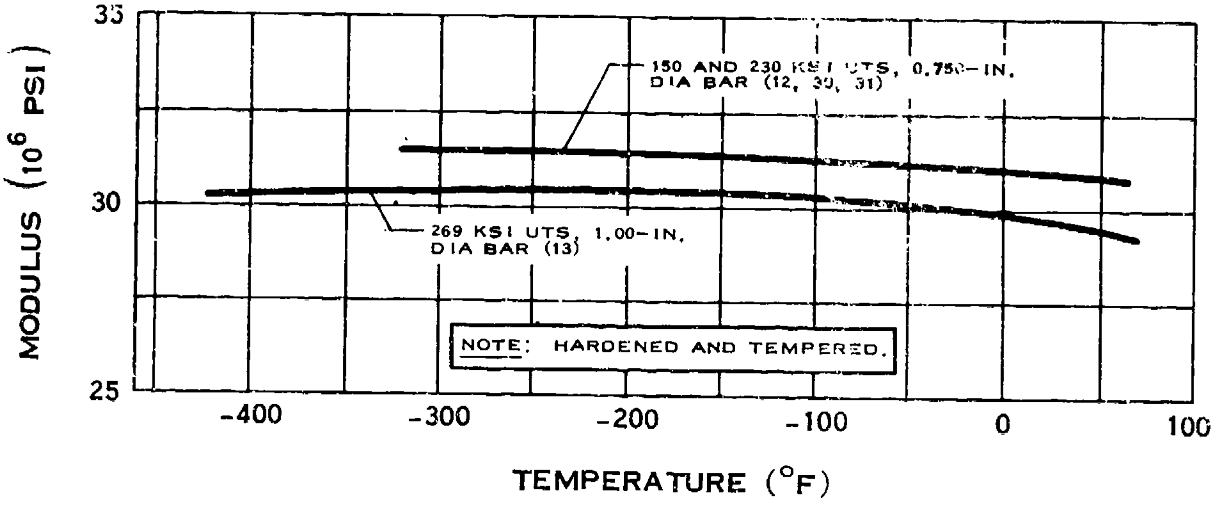
REDUCTION OF AREA OF 4340 STEEL

E.2.j

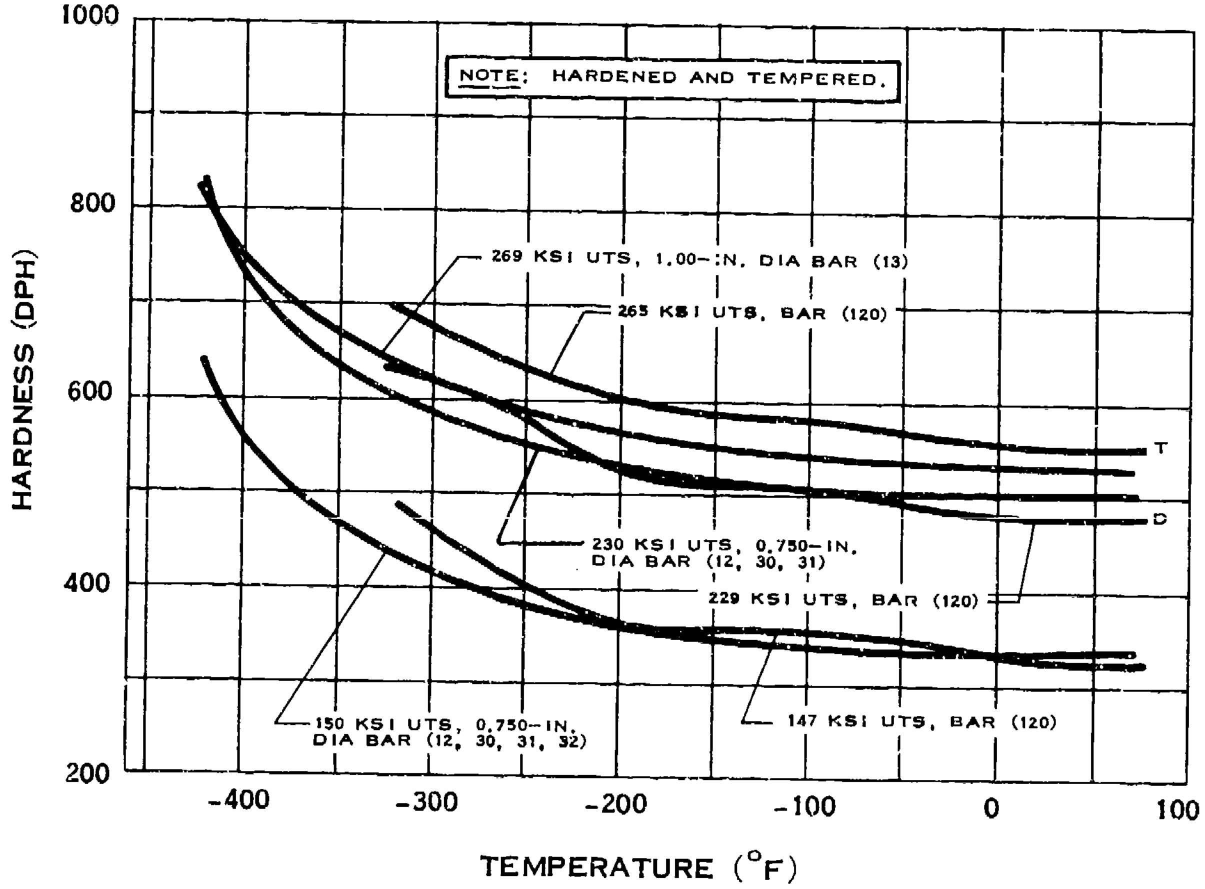


IMPACT STRENGTH OF 4340 STEEL

(7-64)

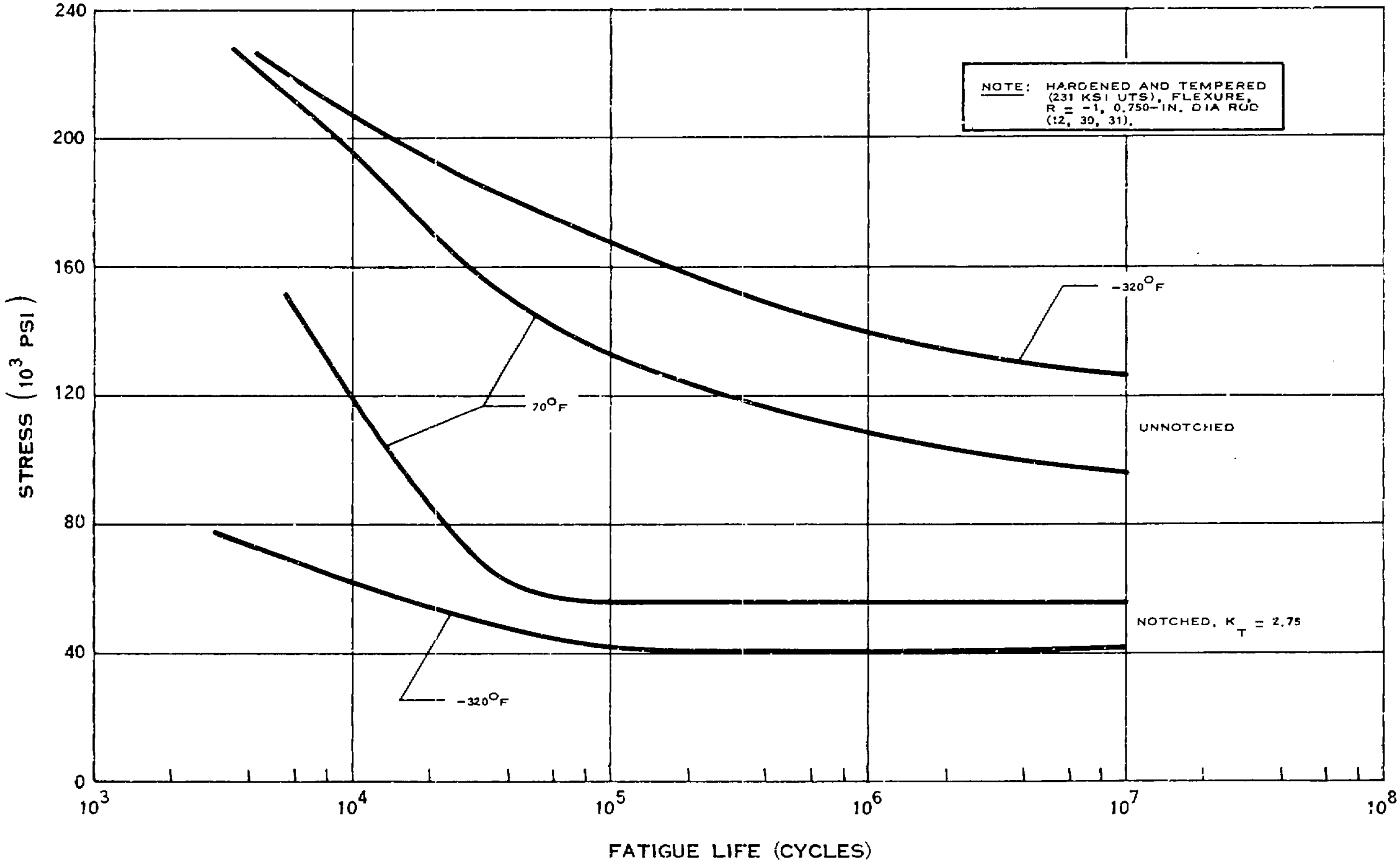


MODULUS OF ELASTICITY OF 4340 STEEL



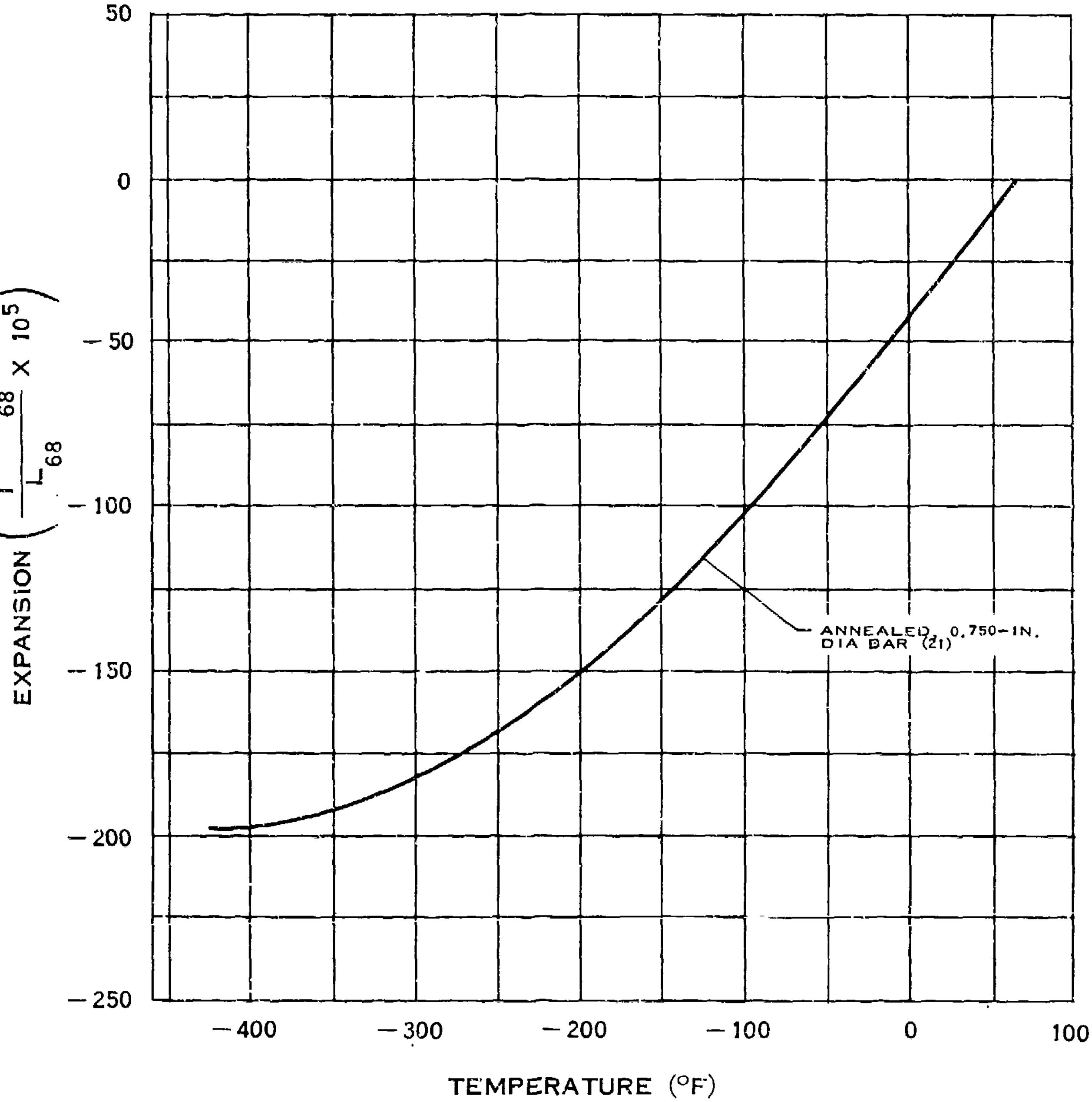
HARDNESS OF 4340 STEEL

(7-65)

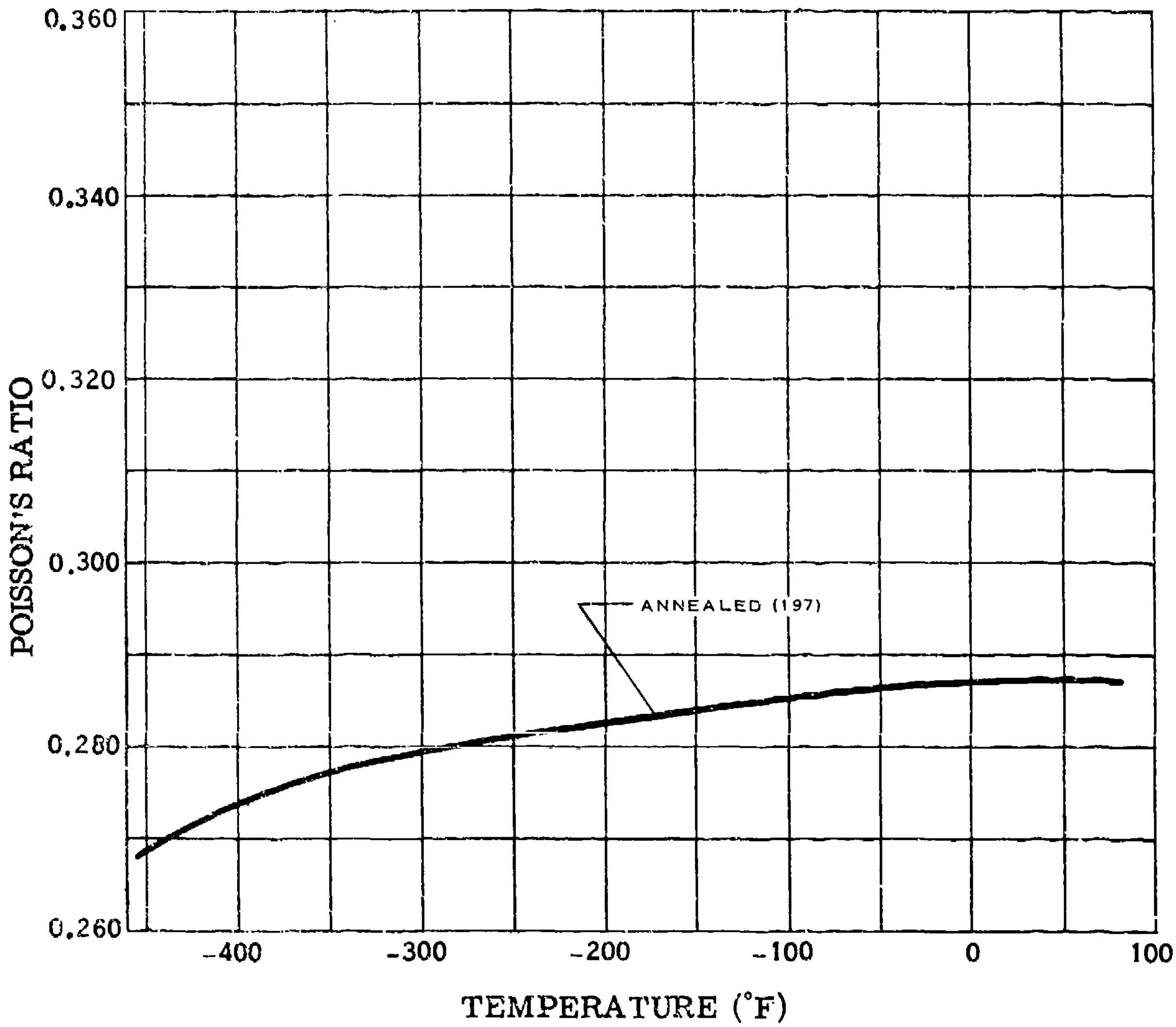


FATIGUE STRENGTH OF 4340 STEEL

(7-64)

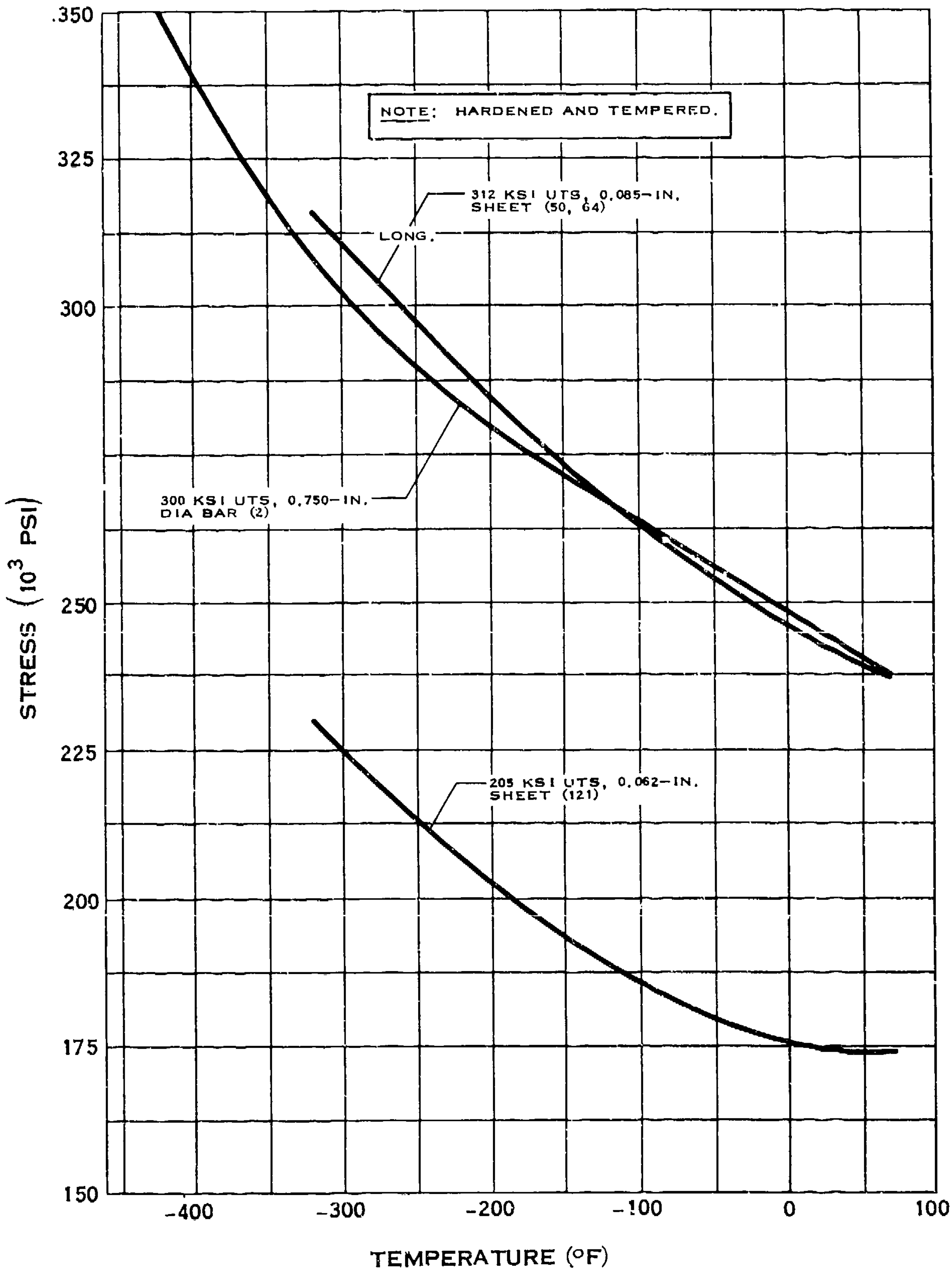


THERMAL EXPANSION OF 4340 STEEL



POISSON'S RATIO OF 4340 STEEL

(6-68)



YIELD STRENGTH OF H-11 (5%Cr) STEEL

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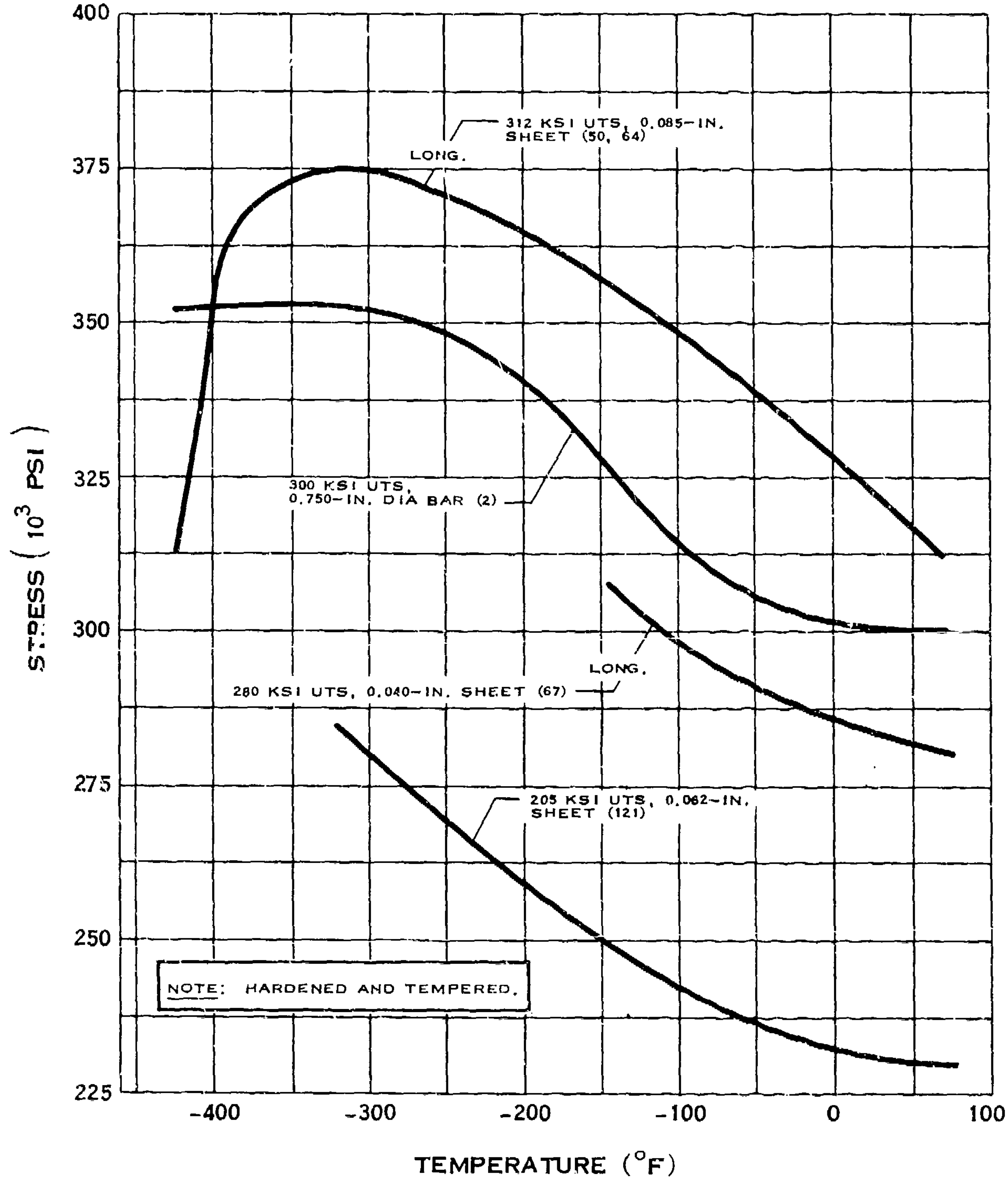
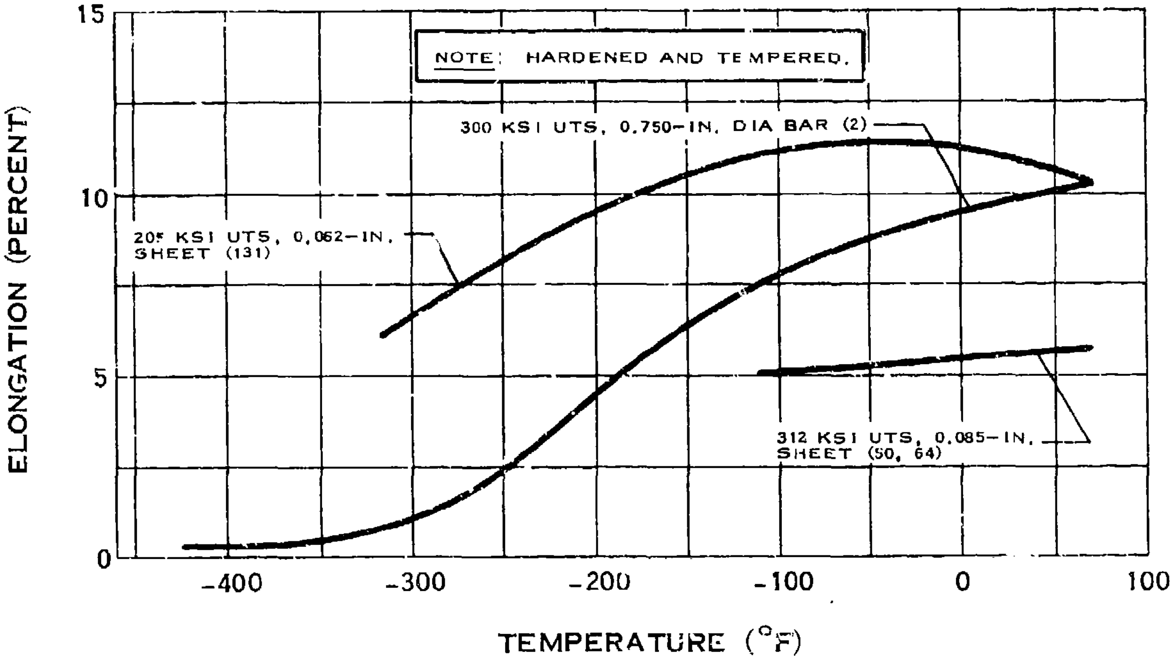
E.3.b

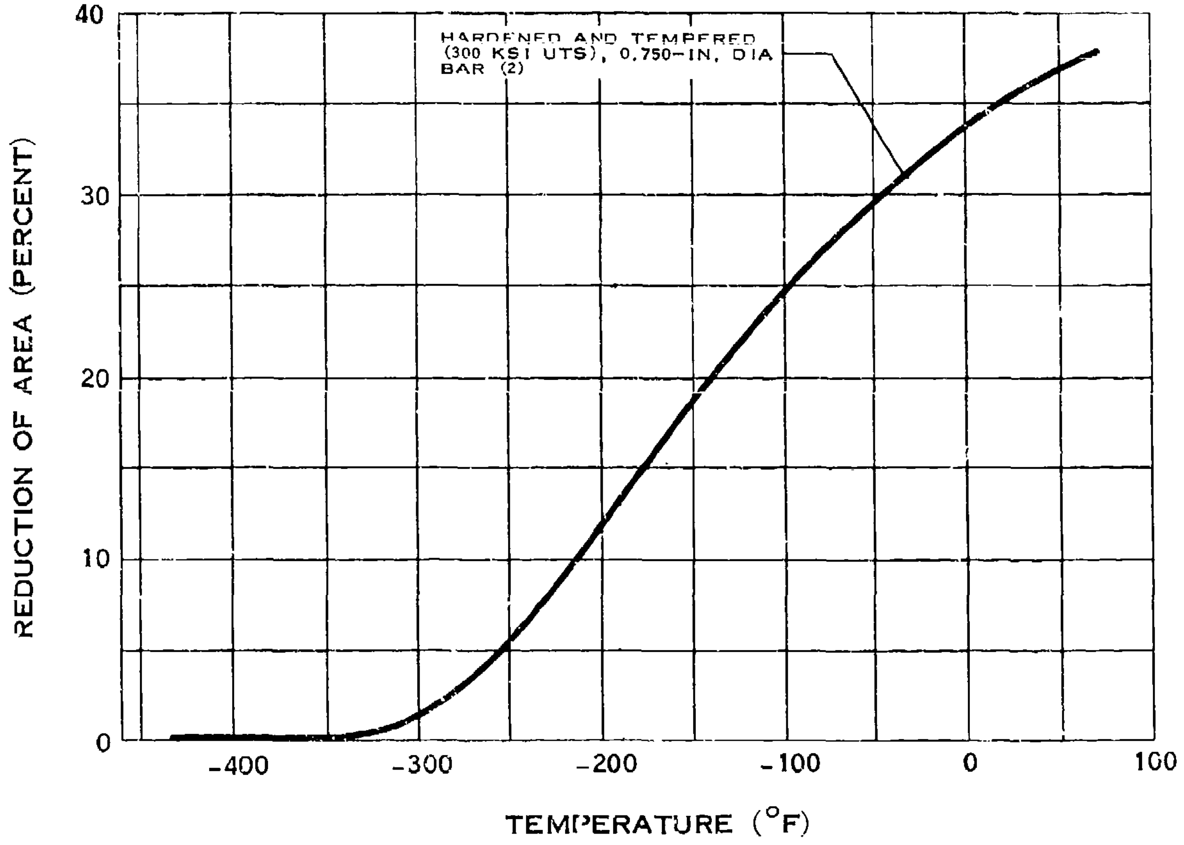


TENSILE STRENGTH OF H-11 (5% Cr) STEEL

(7-65)

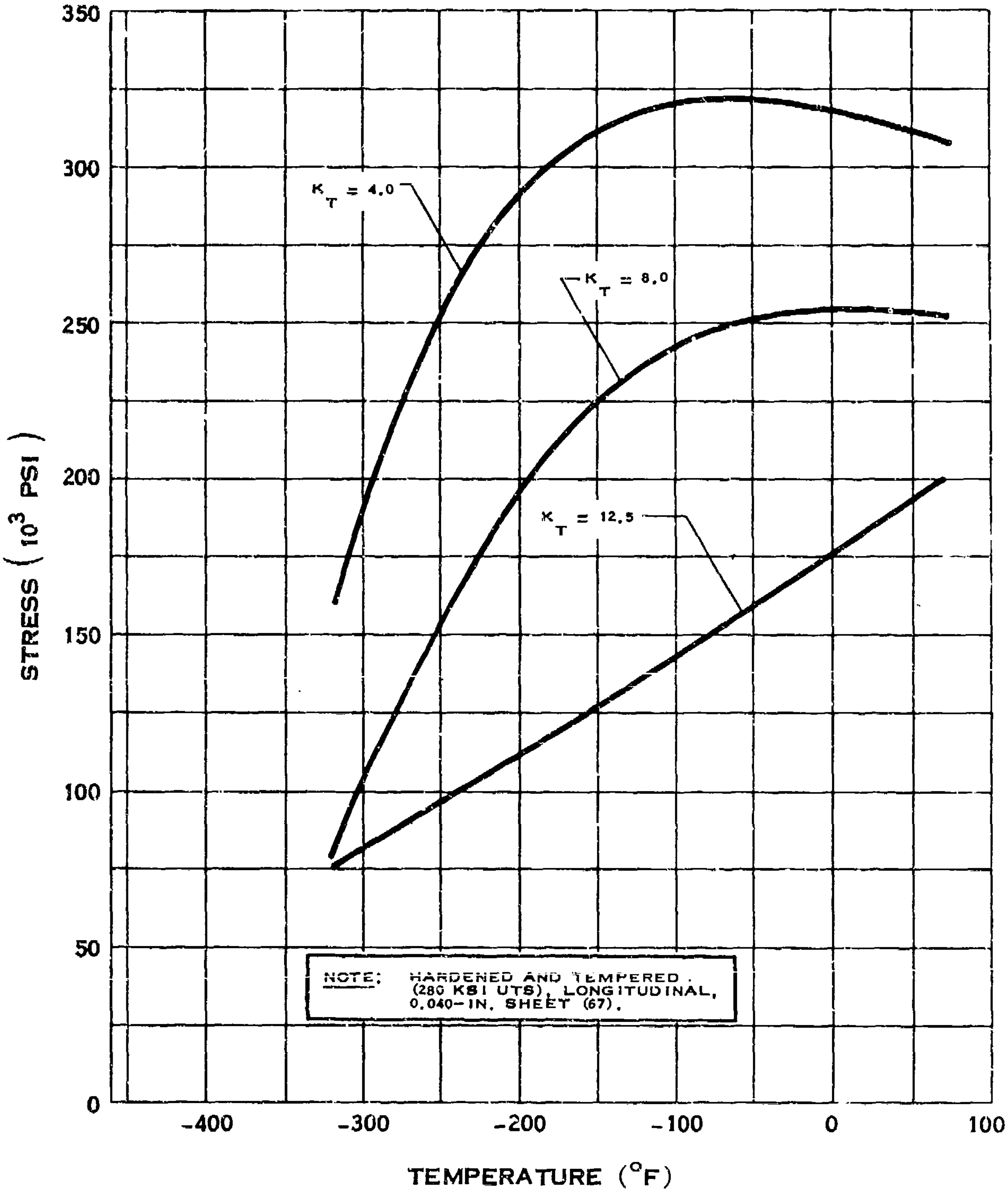


ELONGATION OF H-11 (5% Cr) STEEL



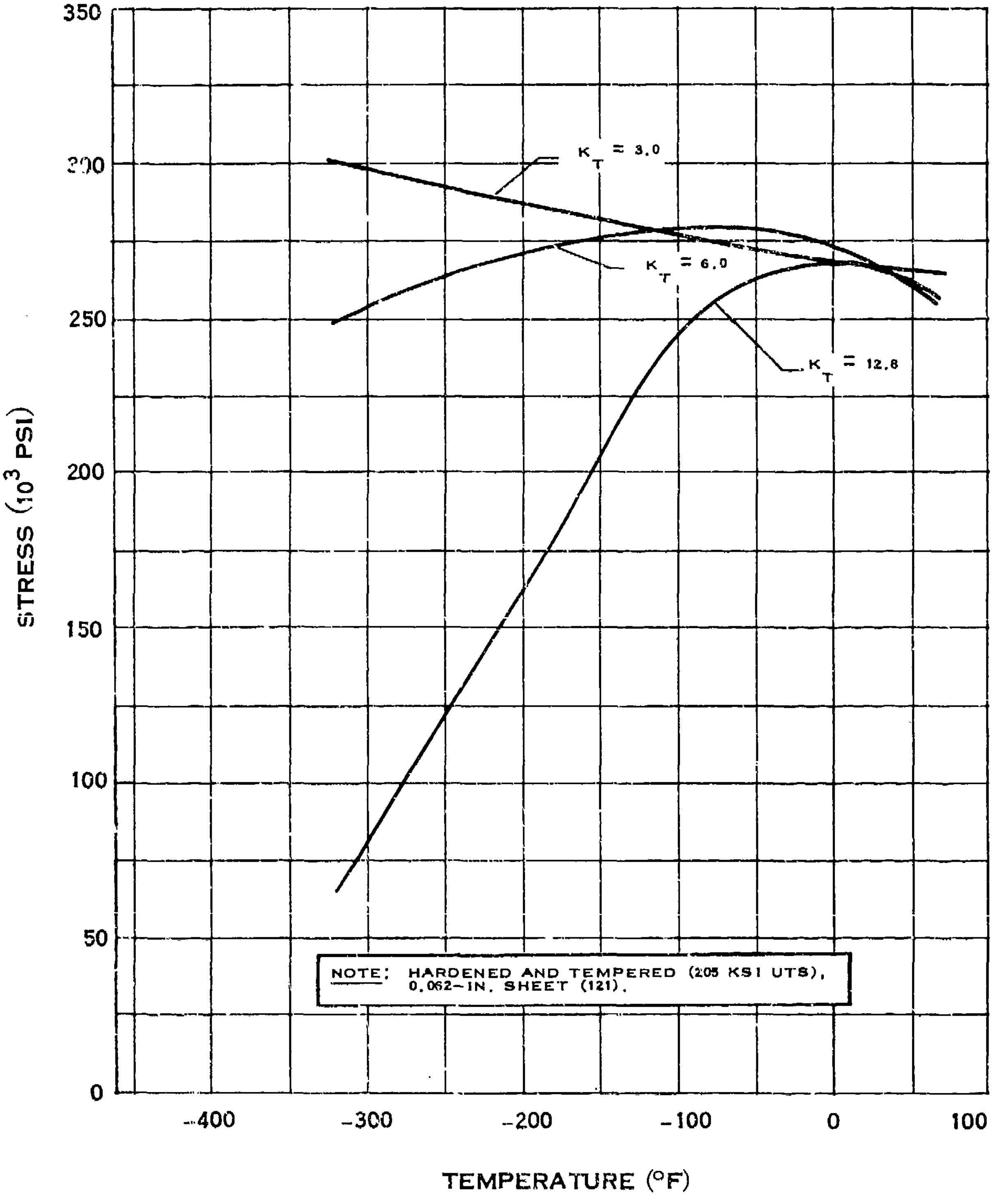
(7-65)

REDUCTION OF AREA OF H-11 (5%Cr) STEEL



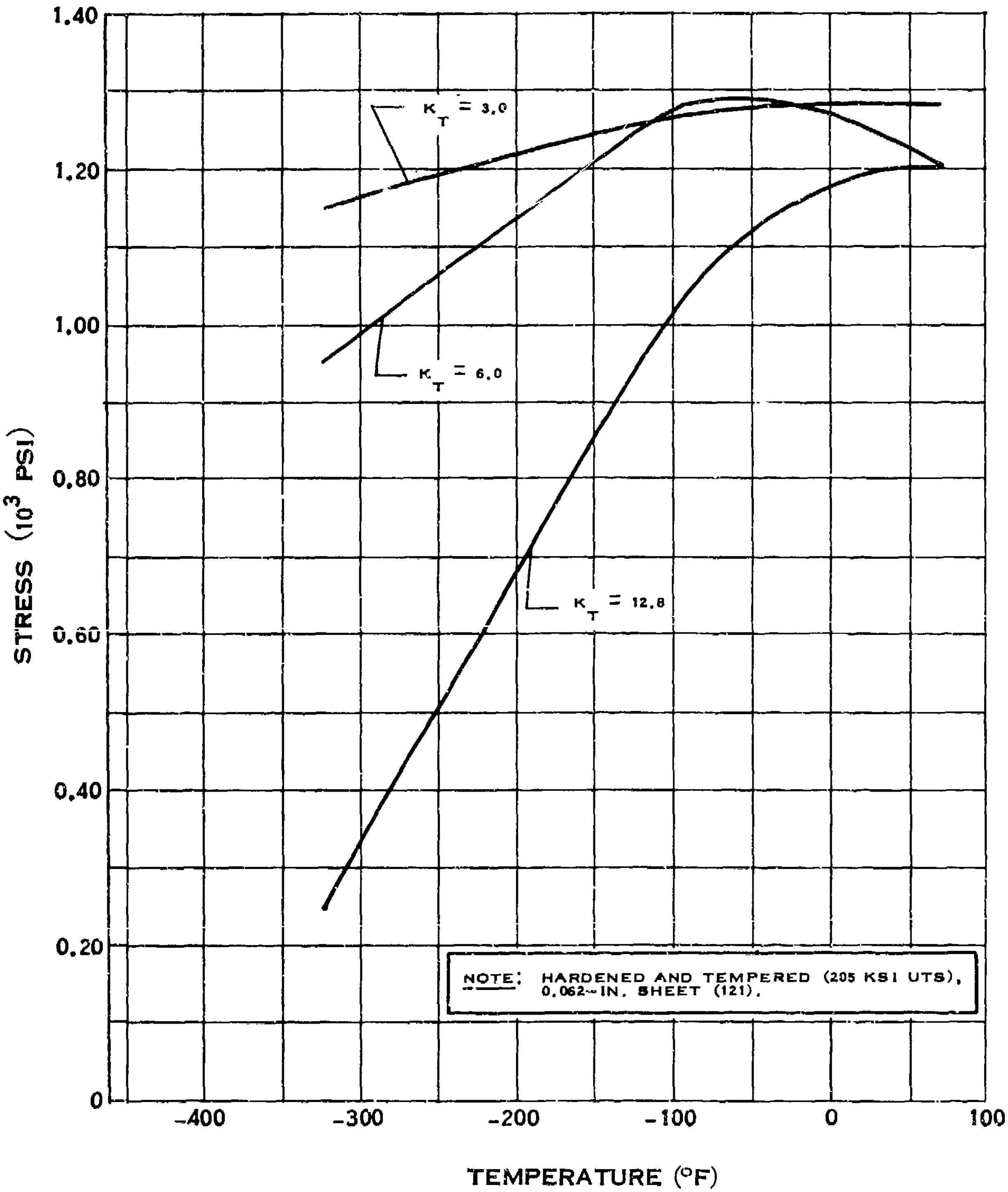
NOTCH TENSILE STRENGTH OF H-11 (5% Cr) STEEL

(7-64)

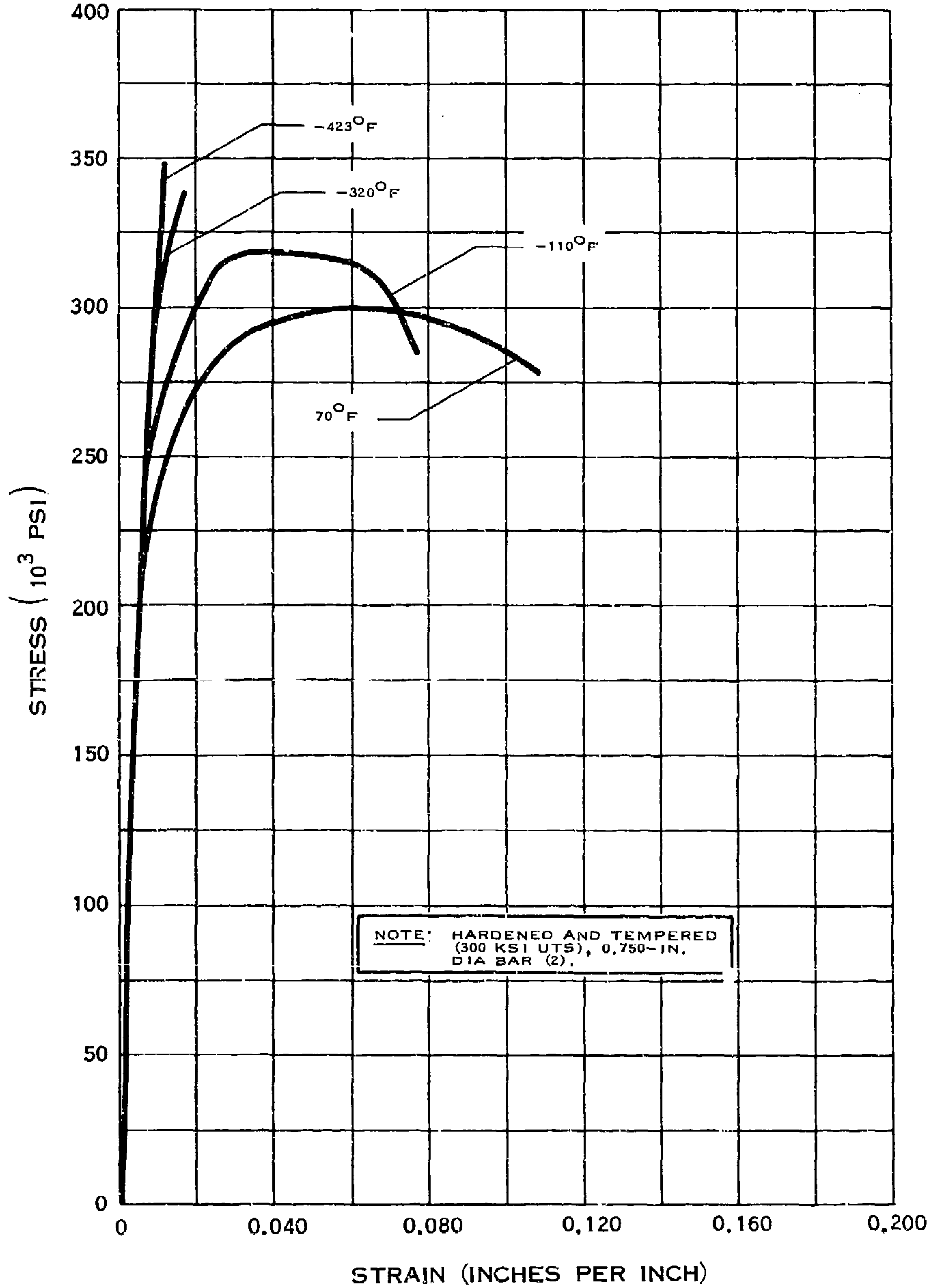


NOTCH TENSILE STRENGTH OF H-11 (5% Cr) STEEL

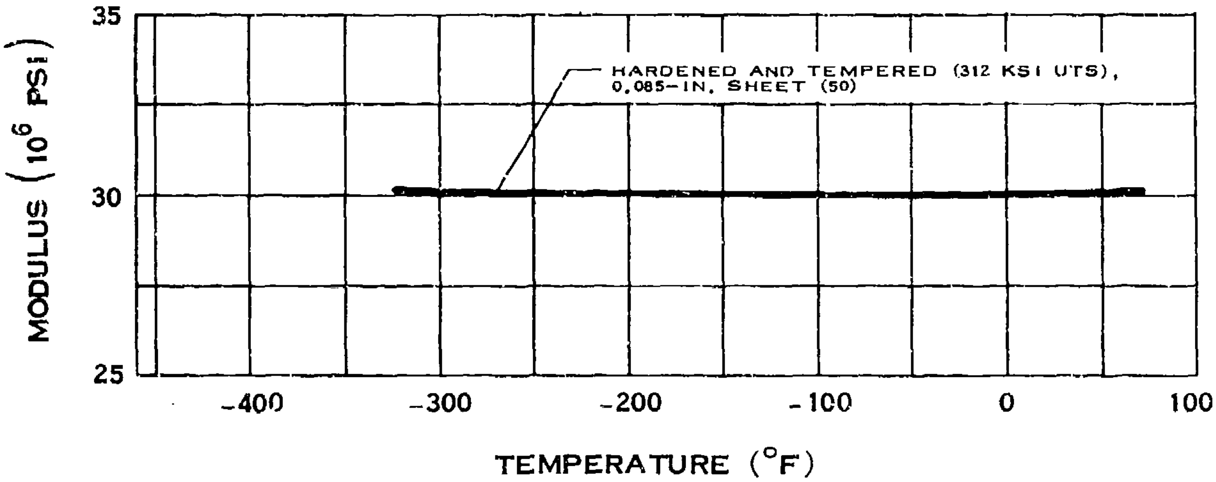
(7-63)



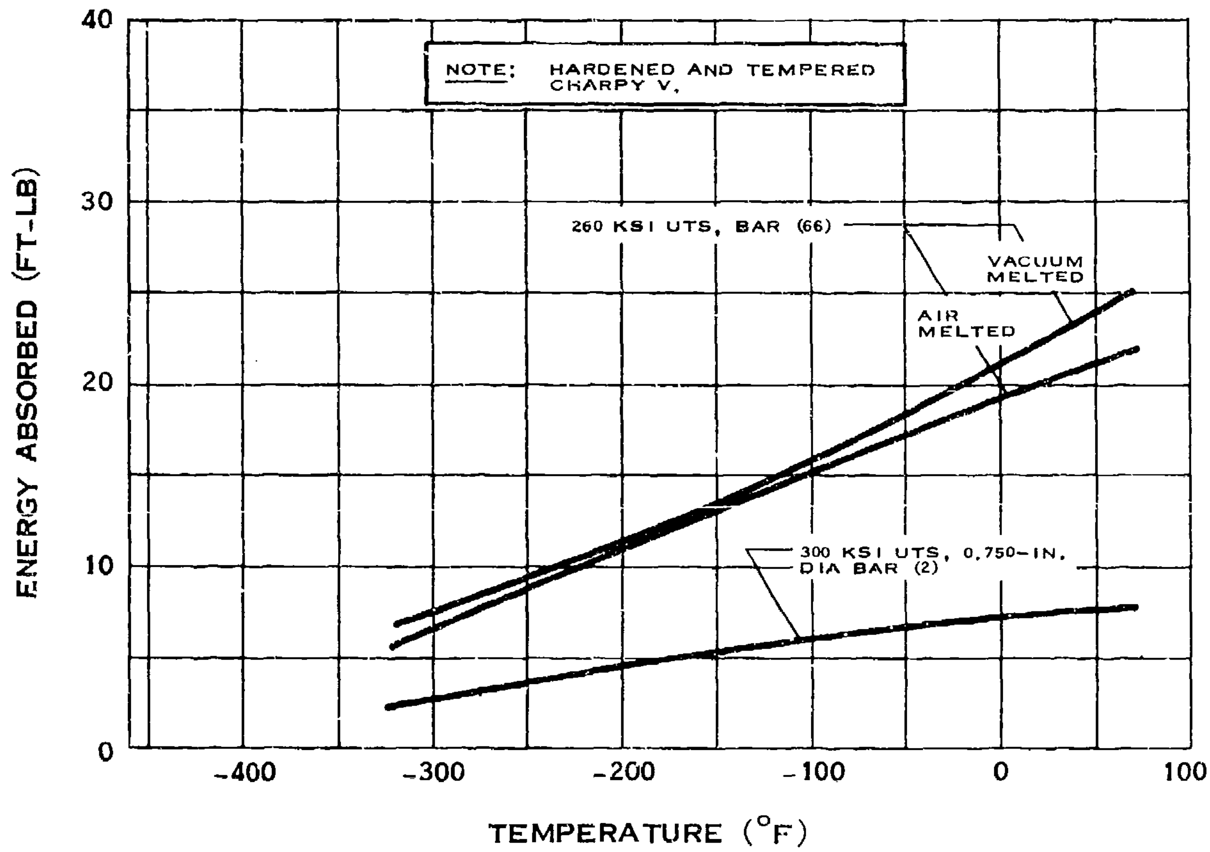
NOTCH STRENGTH RATIO OF H-11 (5% Cr) STEEL



STRESS-STRAIN DIAGRAM FOR H11 (5%Cr) STEEL

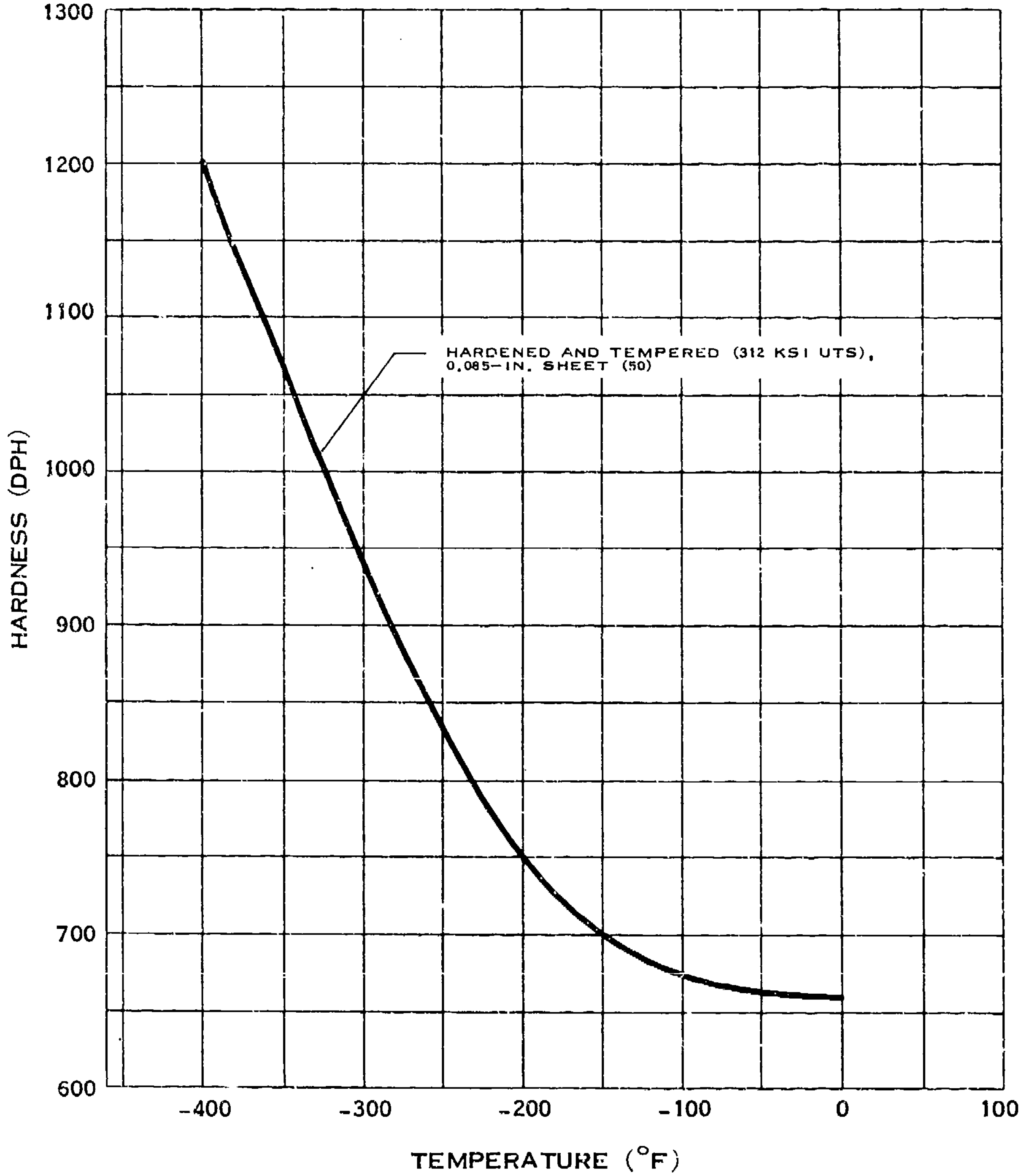


MODULUS OF ELASTICITY OF H-11 (5% Cr) STEEL



IMPACT STRENGTH OF H-11 (5% Cr) STEEL

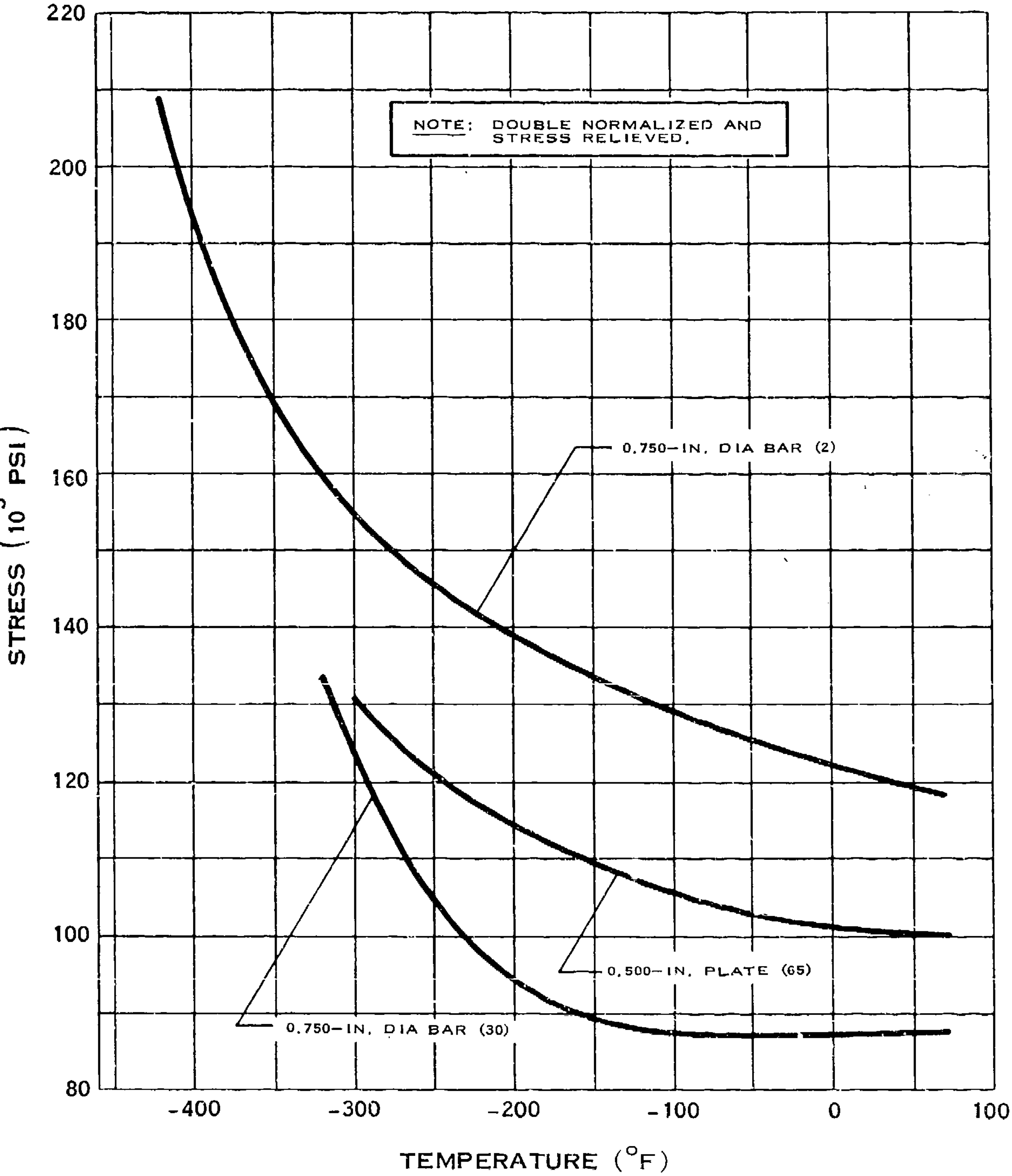
E.3.k



HARDNESS OF H-11 (5% Cr) STEEL

(7-64)

E.4.a



YIELD STRENGTH OF 2800 (9%Ni) STEEL

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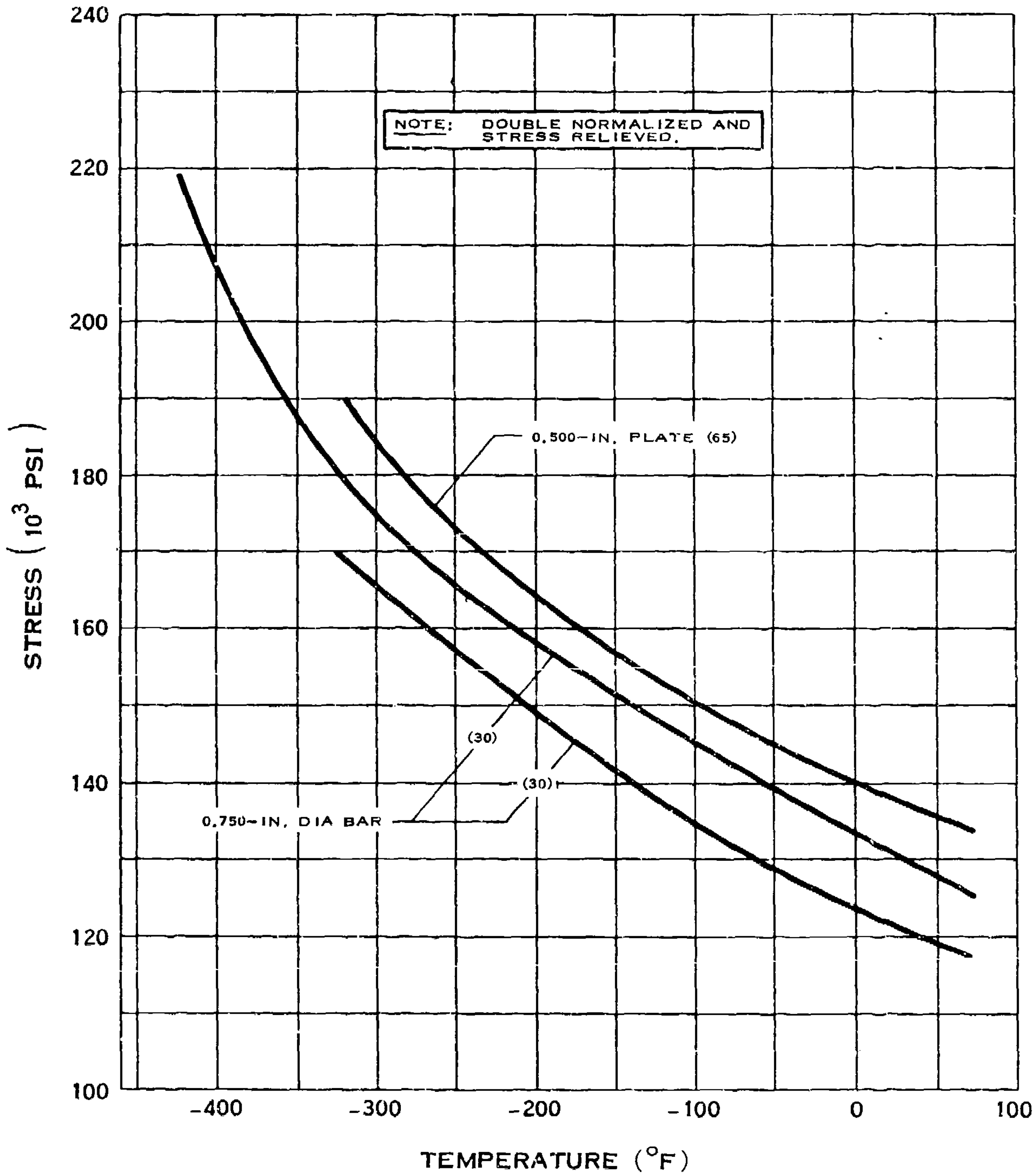
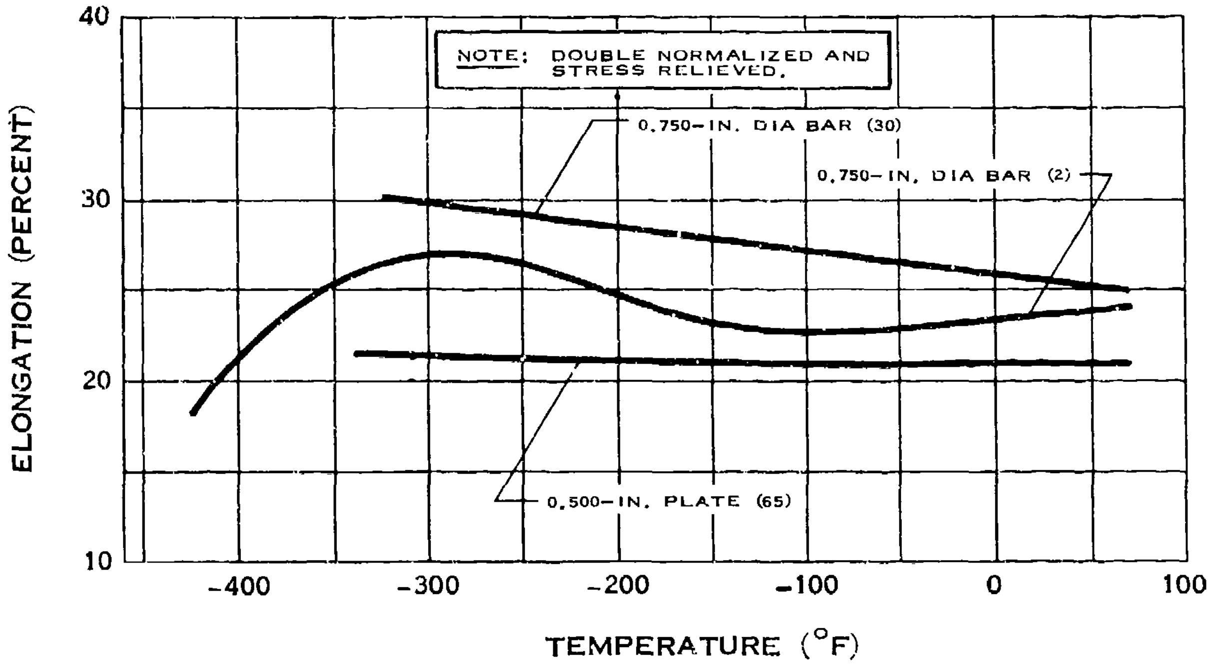
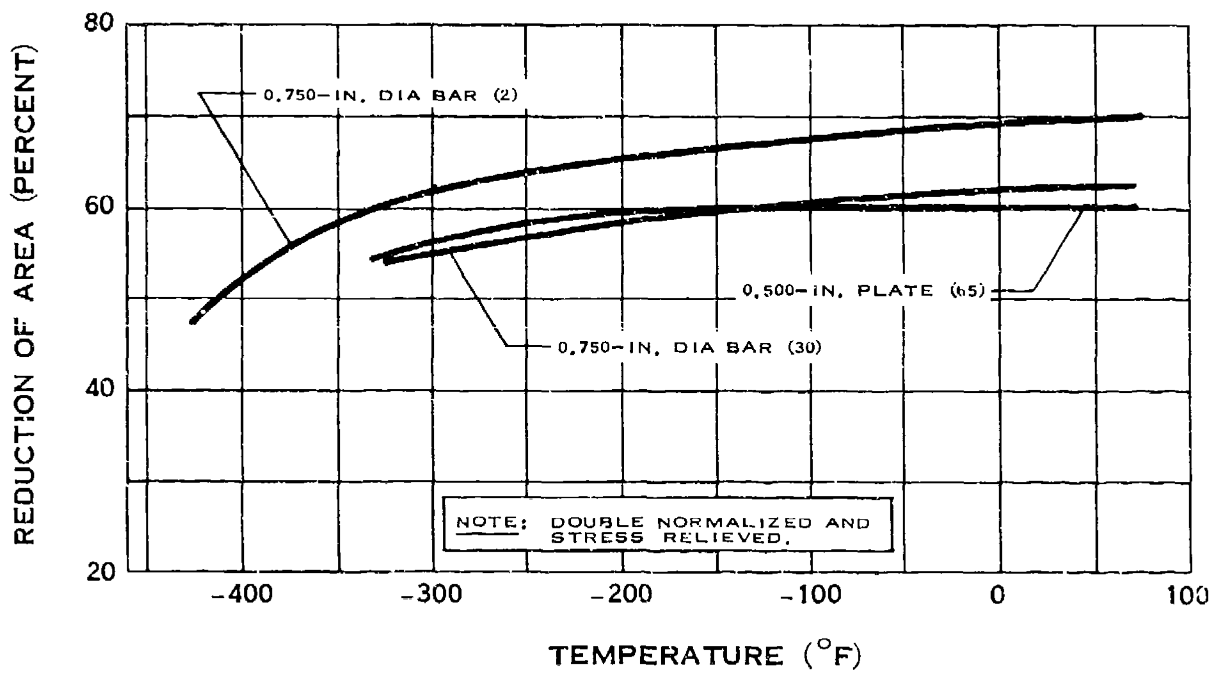
E.4.b



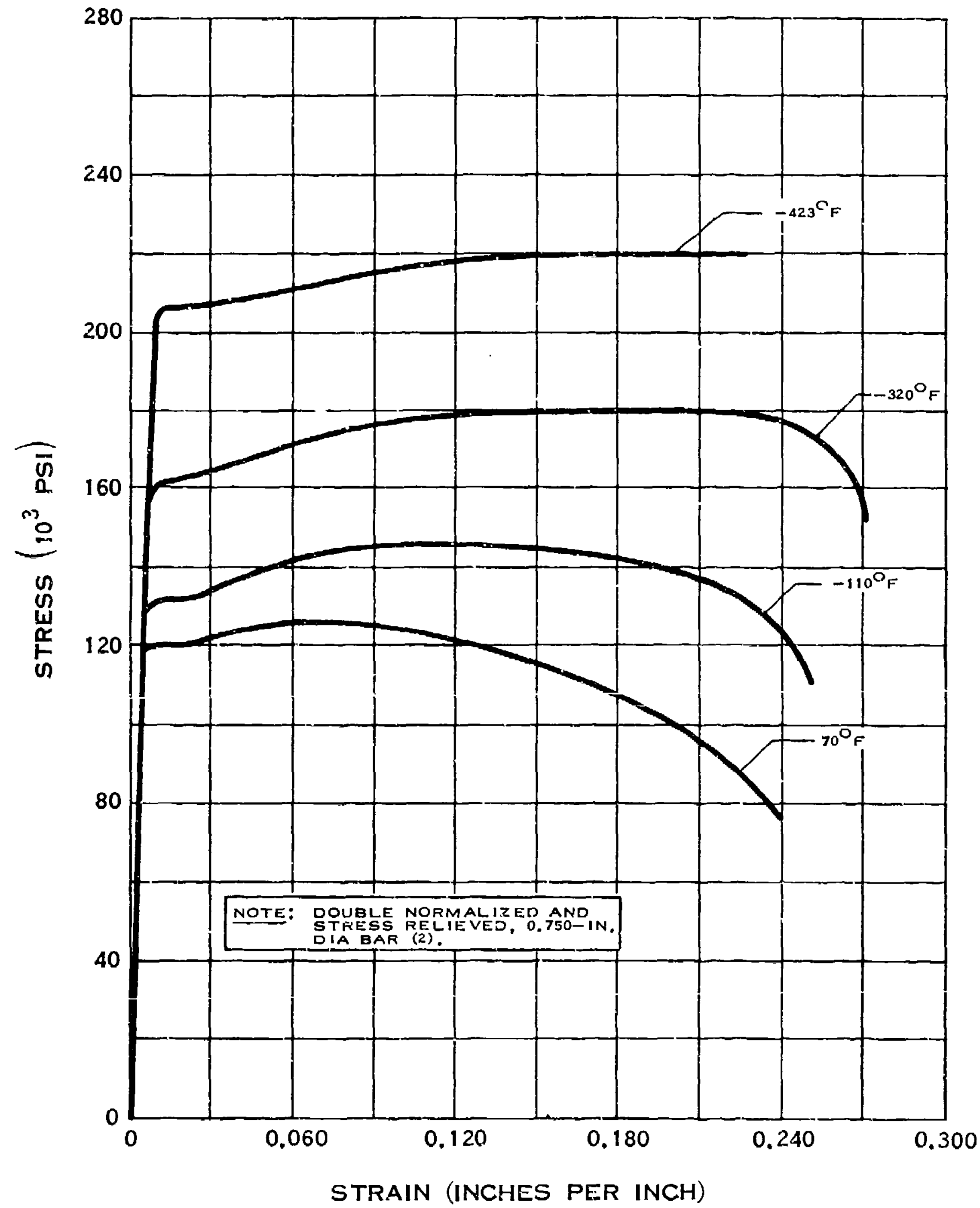
TENSILE STRENGTH OF 2800 (9% Ni) STEEL



ELONGATION OF 2800 (9% Ni) STEEL

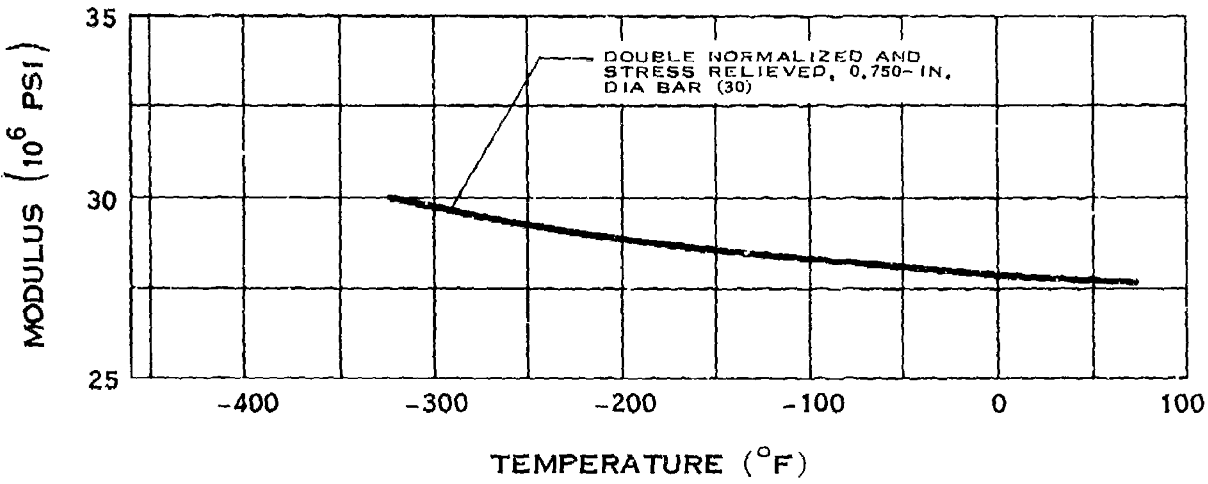


REDUCTION OF AREA OF 2800 (9% Ni) STEEL

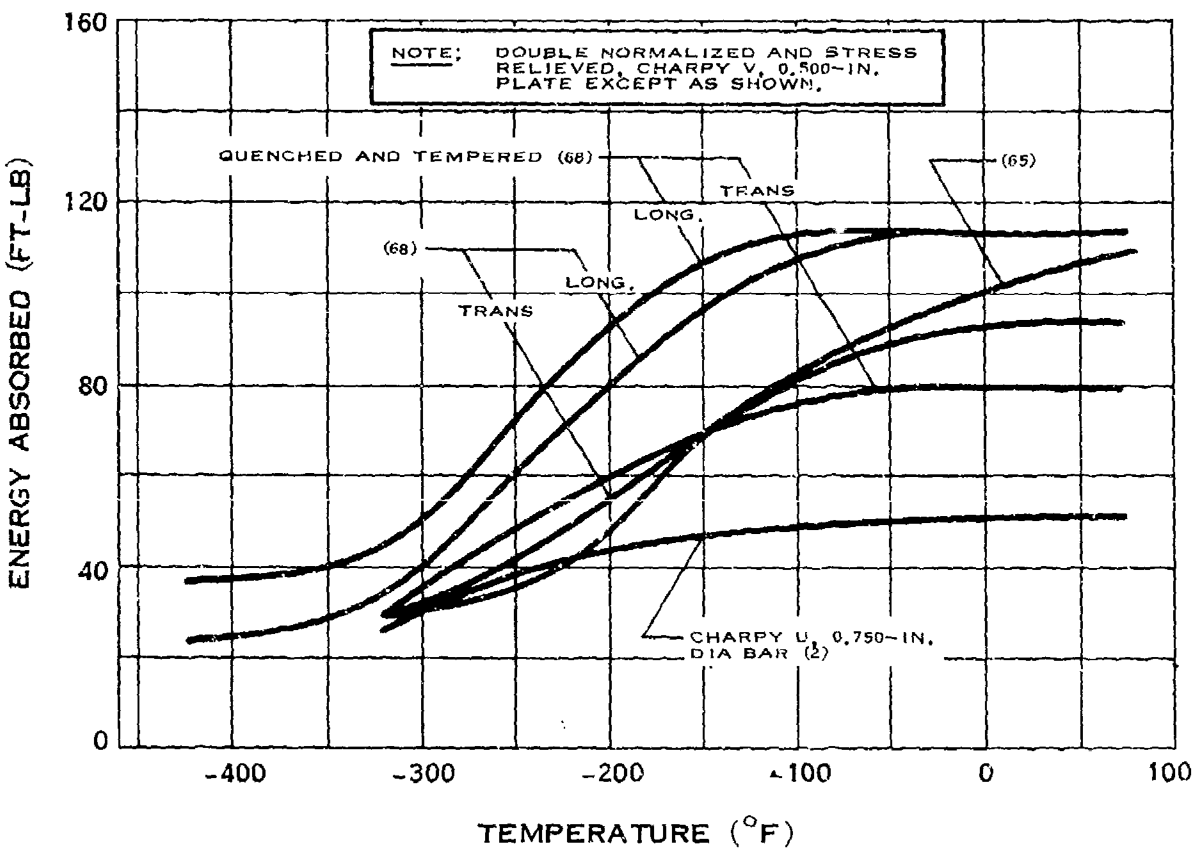


STRESS-STRAIN DIAGRAM FOR 2800 (9%Ni) STEEL

(7-64)

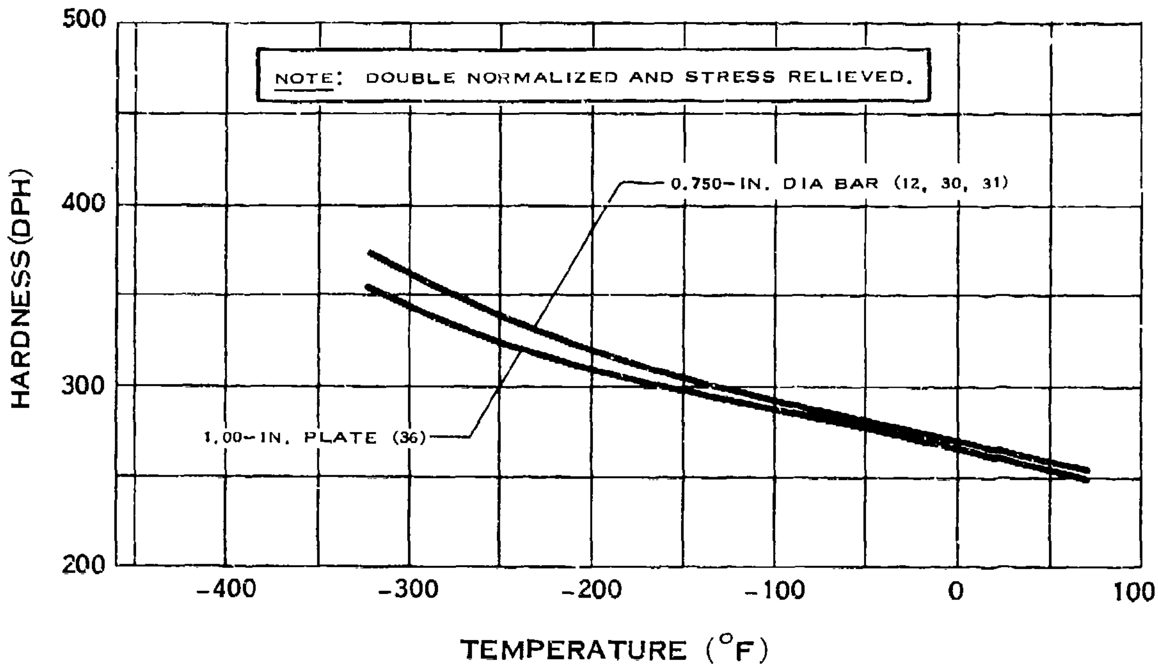


MODULUS OF ELASTICITY OF 2800 (9% Ni) STEEL



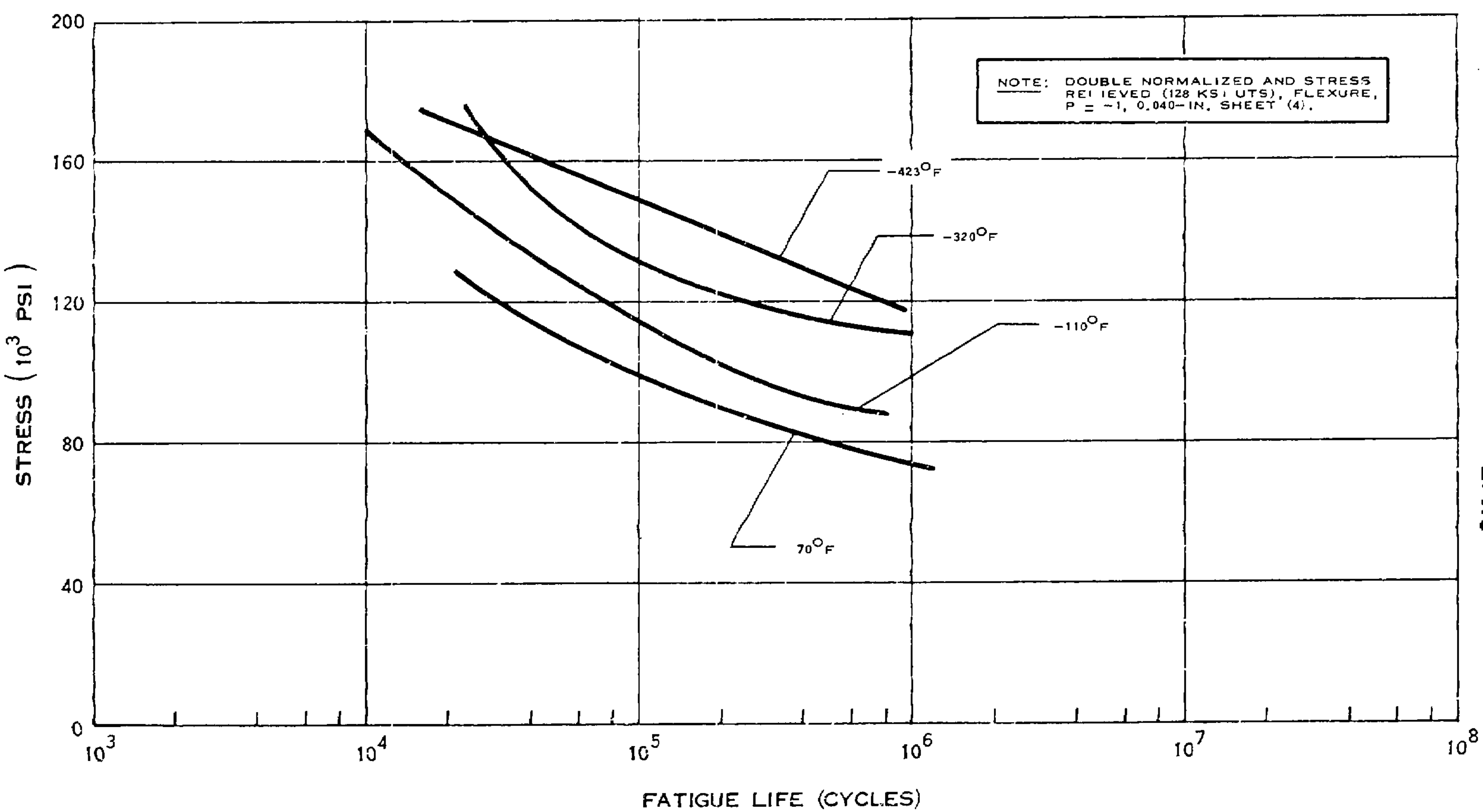
IMPACT STRENGTH OF 2800 (9% Ni) STEEL

E.4.k



HARDNESS OF 2800 (9% Ni) STEEL

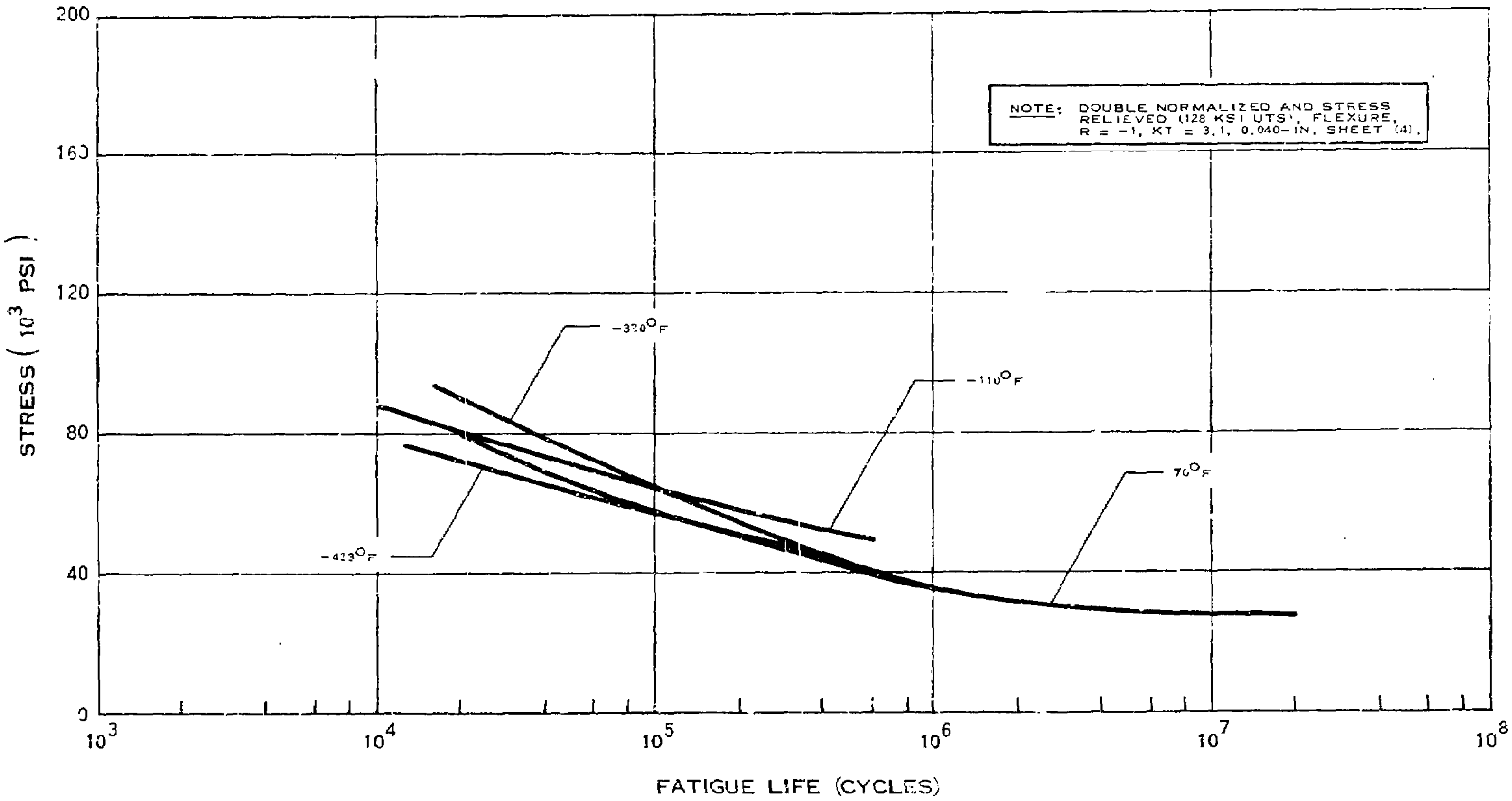
(7-64)



FATIGUE STRENGTH OF 2800 (9%Ni) STEEL

(7-64)

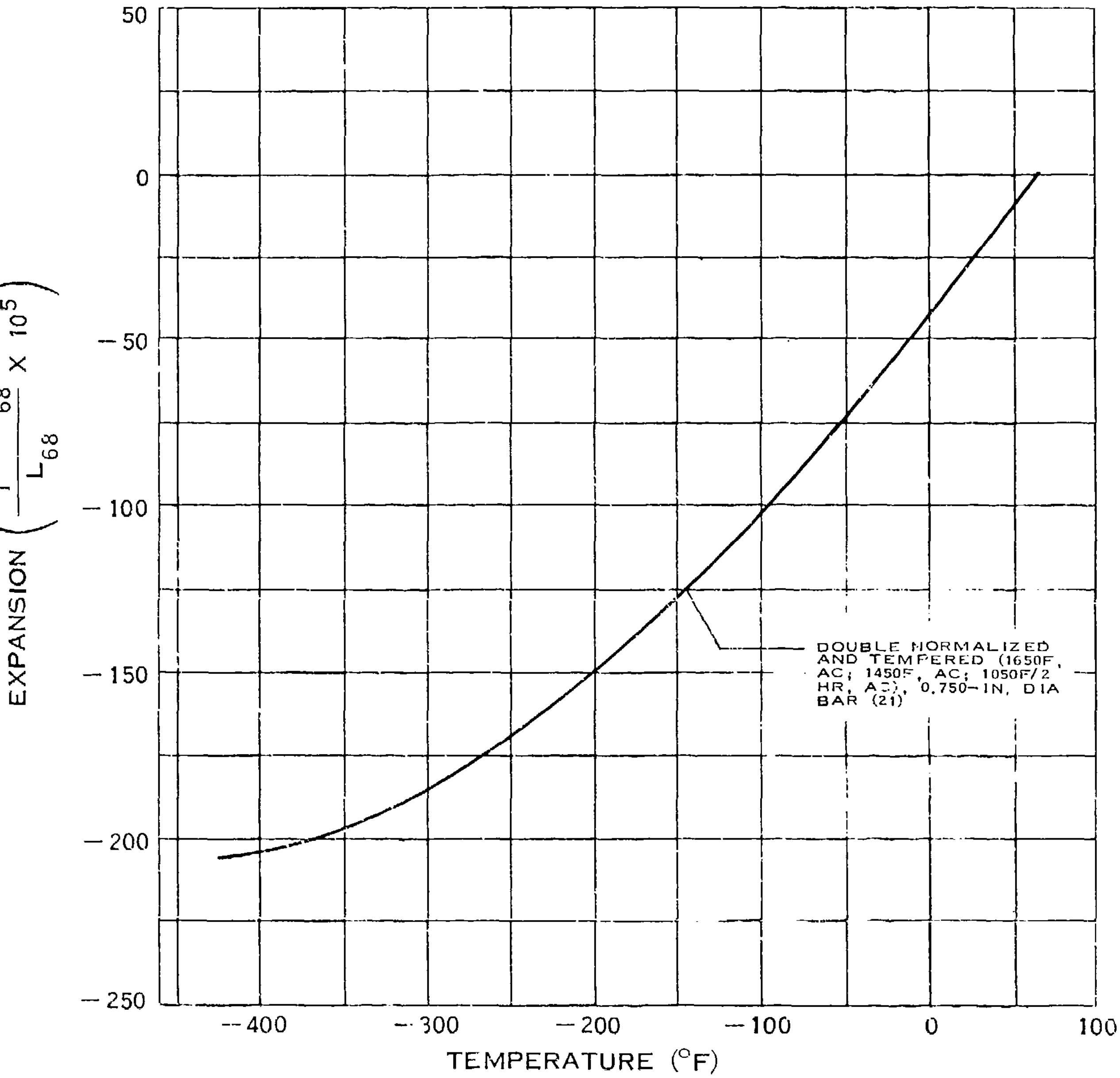
E.4.o-1



NOTCH FATIGUE STRENGTH OF 2800 (9%Ni) STEEL

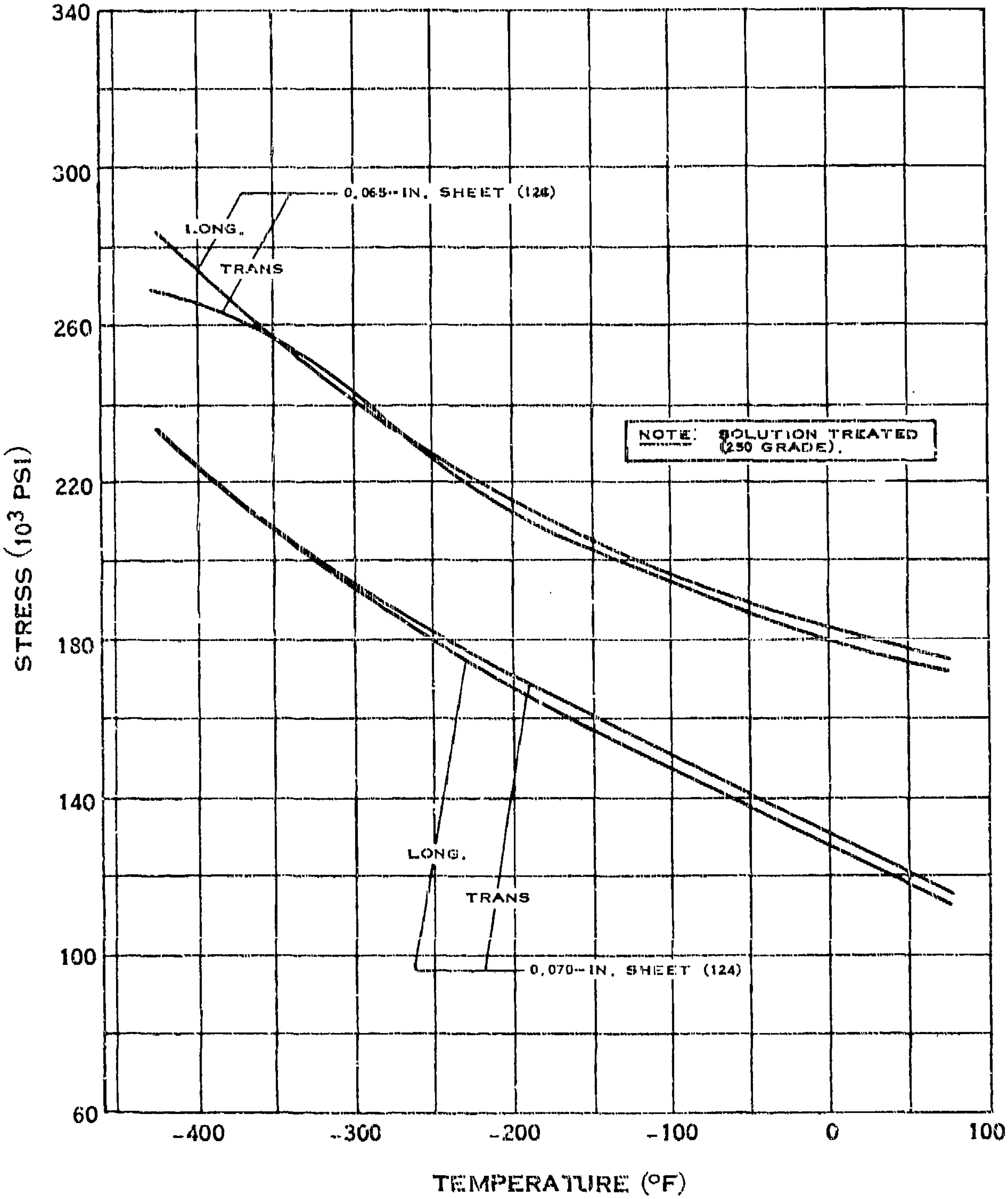
(7−64)

E.4.t



THERMAL EXPANSION OF 2800 (9% Ni) STEEL

(7-64)



YIELD STRENGTH OF 18% Ni MARAGING STEEL

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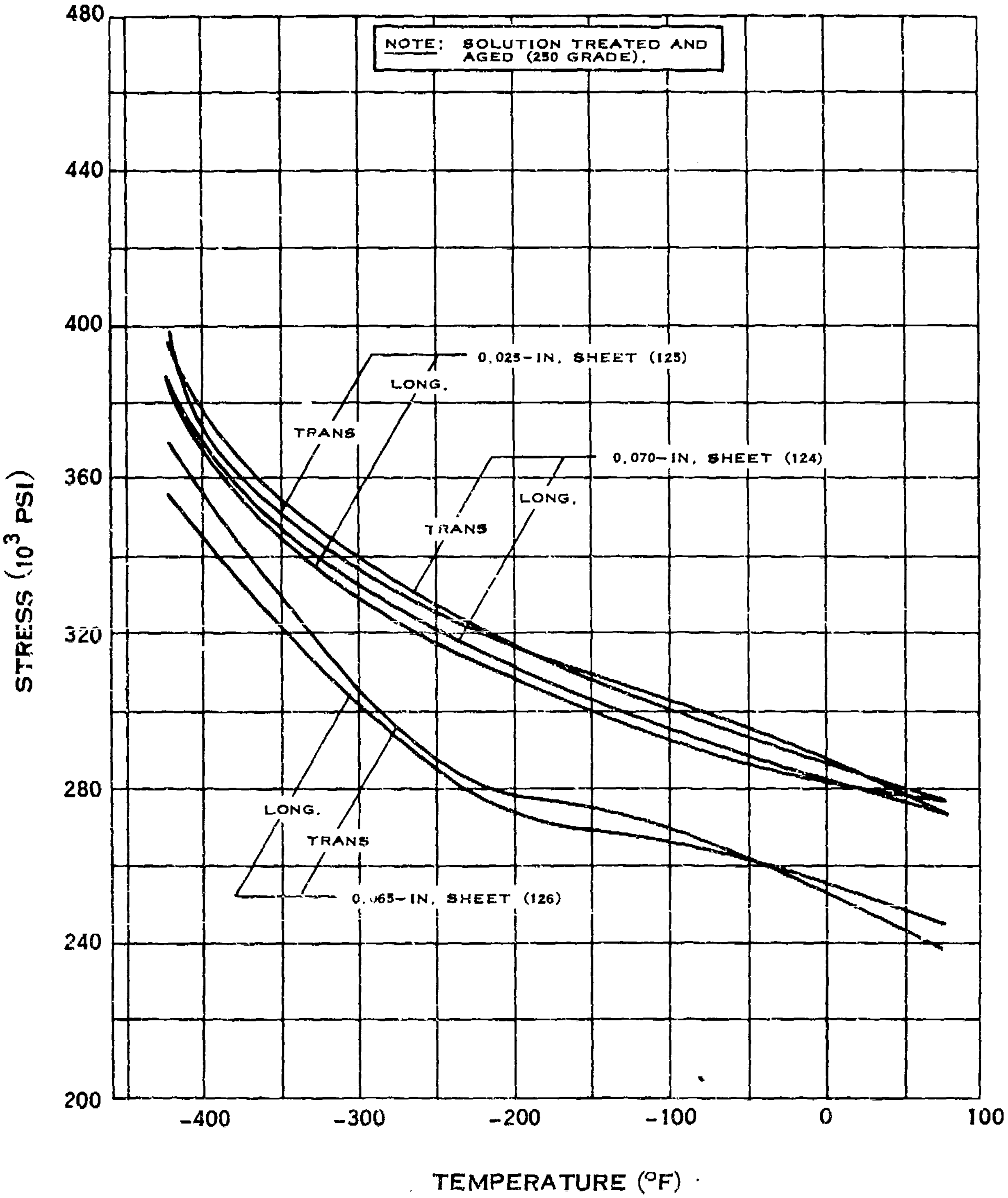
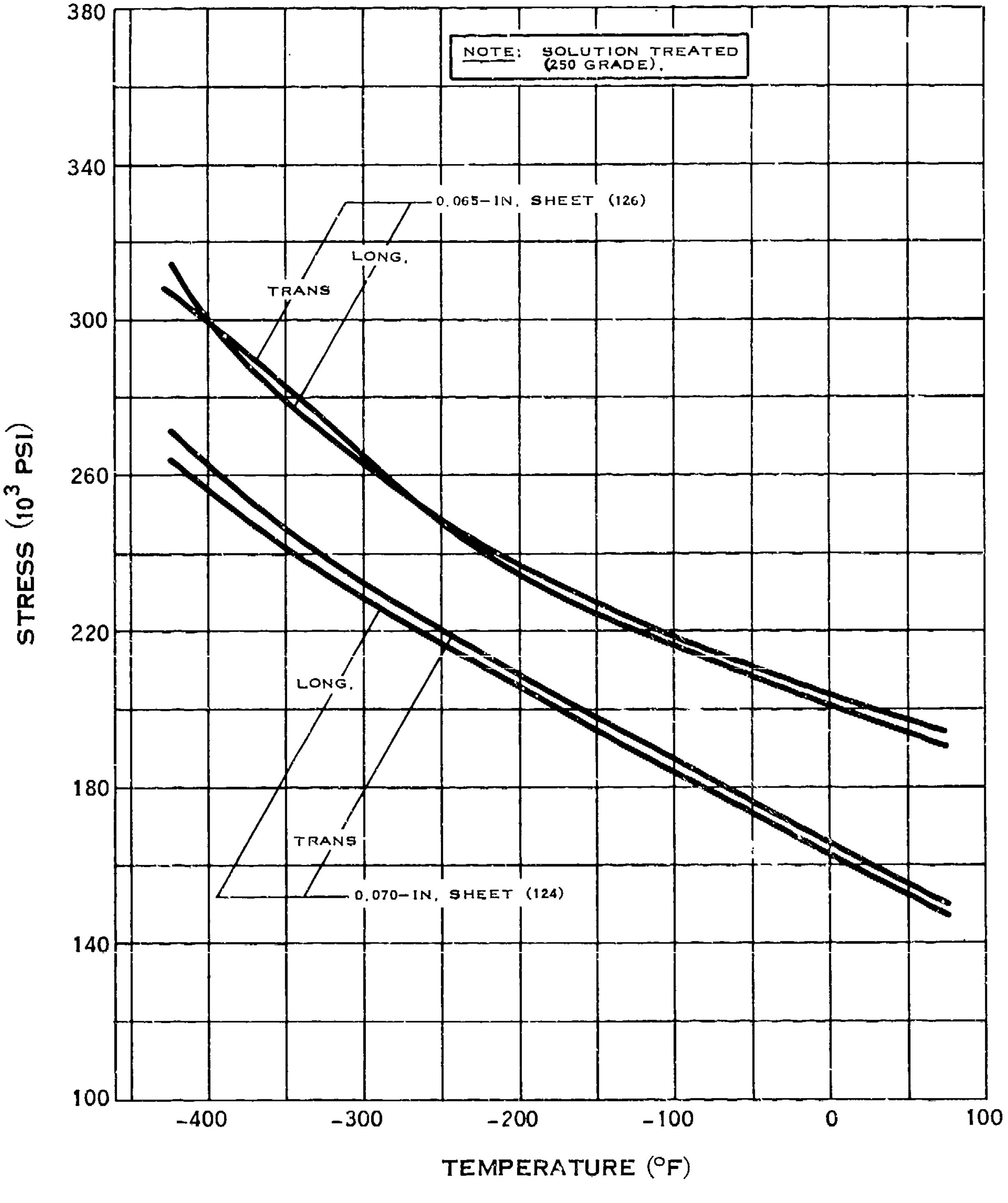
E.5.a-1

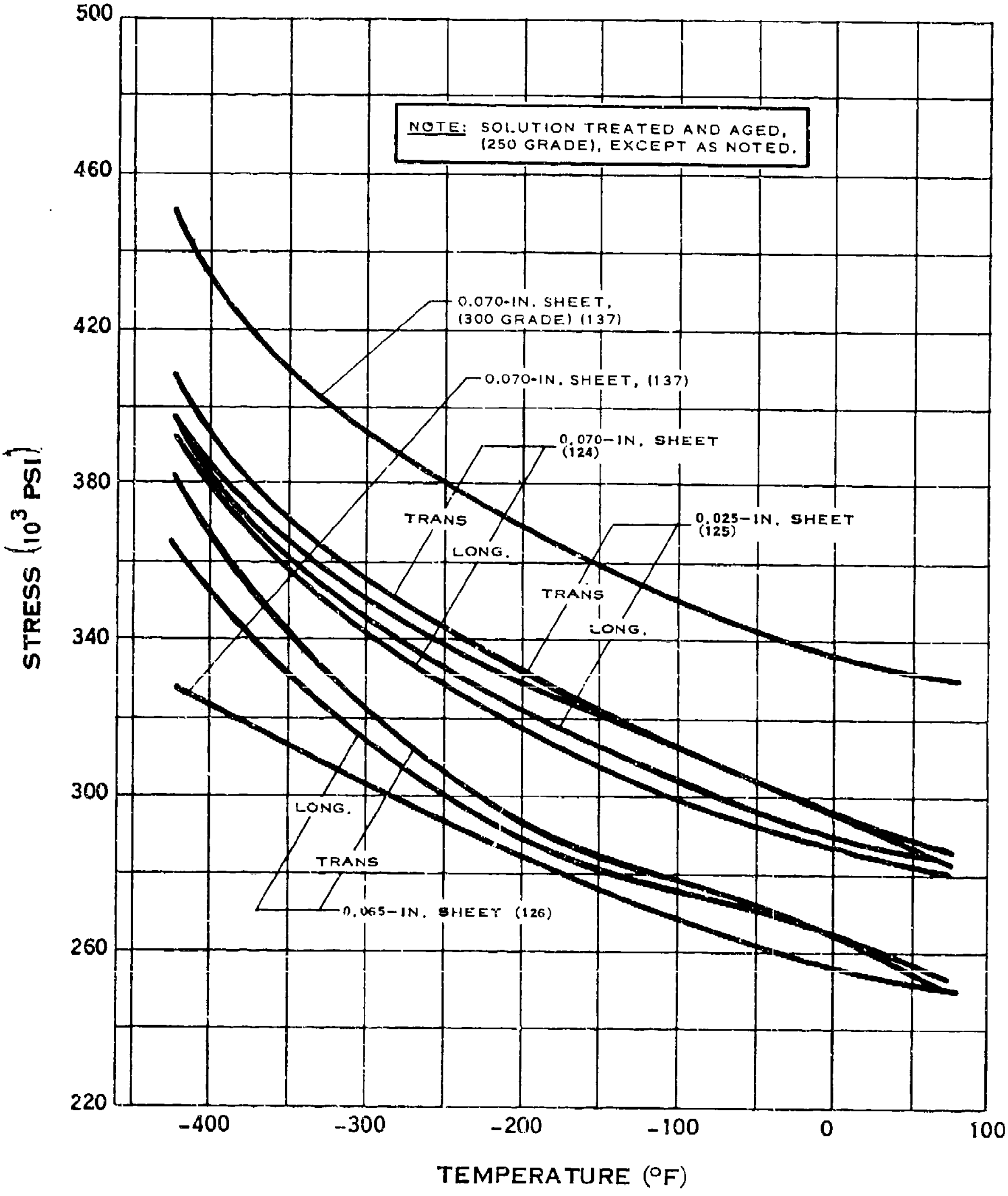


YIELD STRENGTH OF 18% Ni MARAGING STEEL

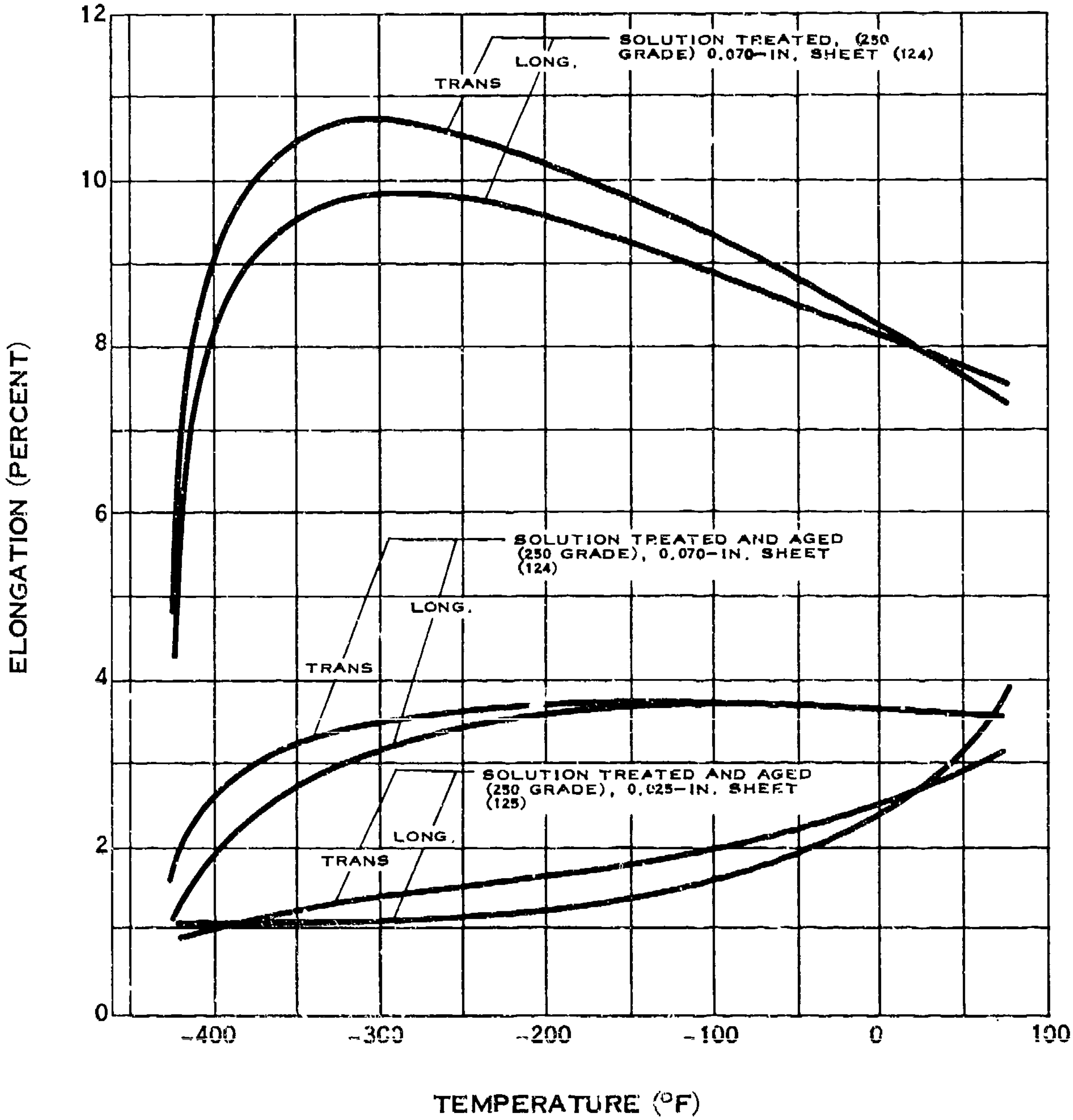


TENSILE STRENGTH OF 18% Ni MARAGING STEEL

(7-65)

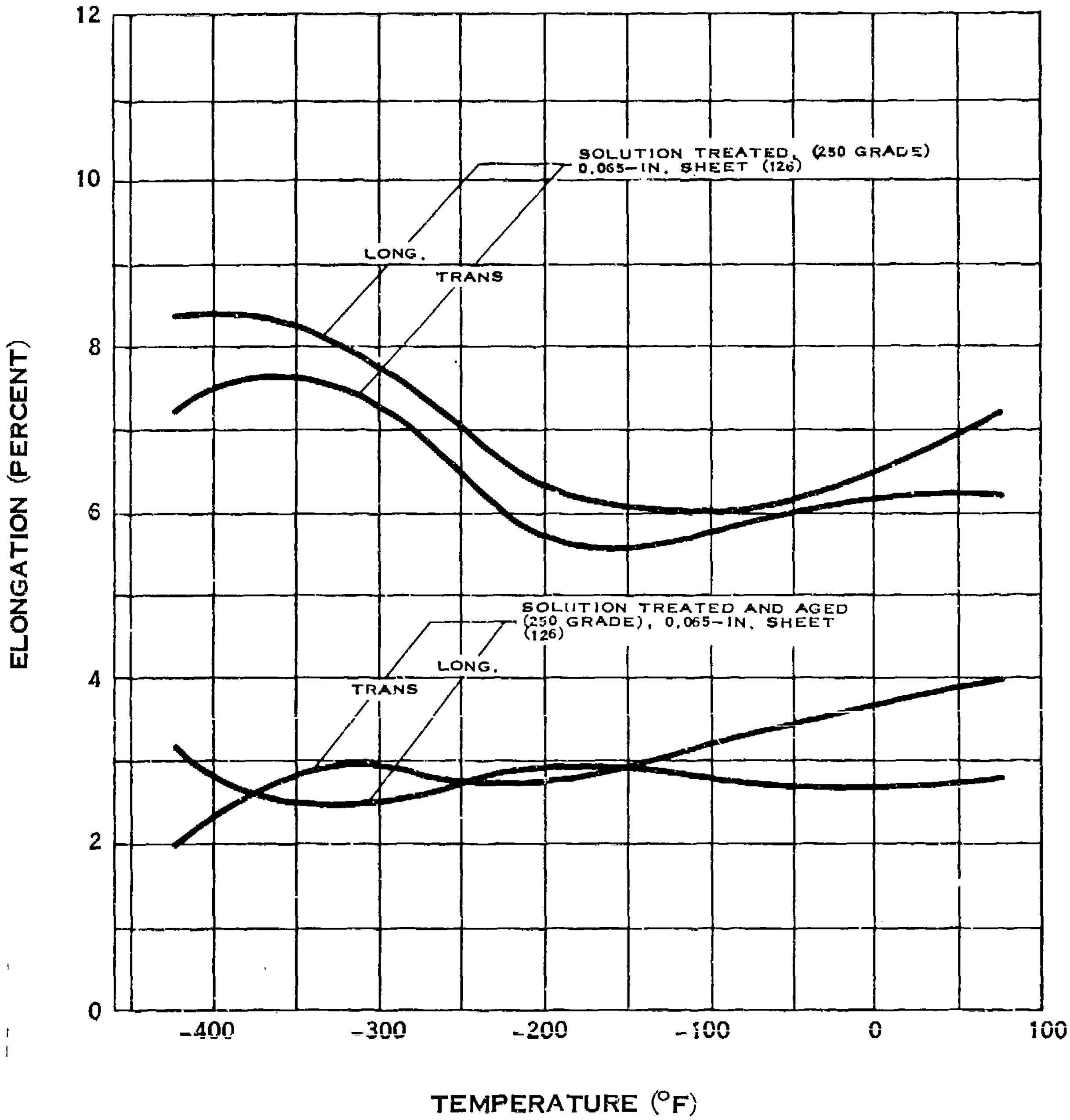


TENSILE STRENGTH OF 18% Ni MARAGING STEEL



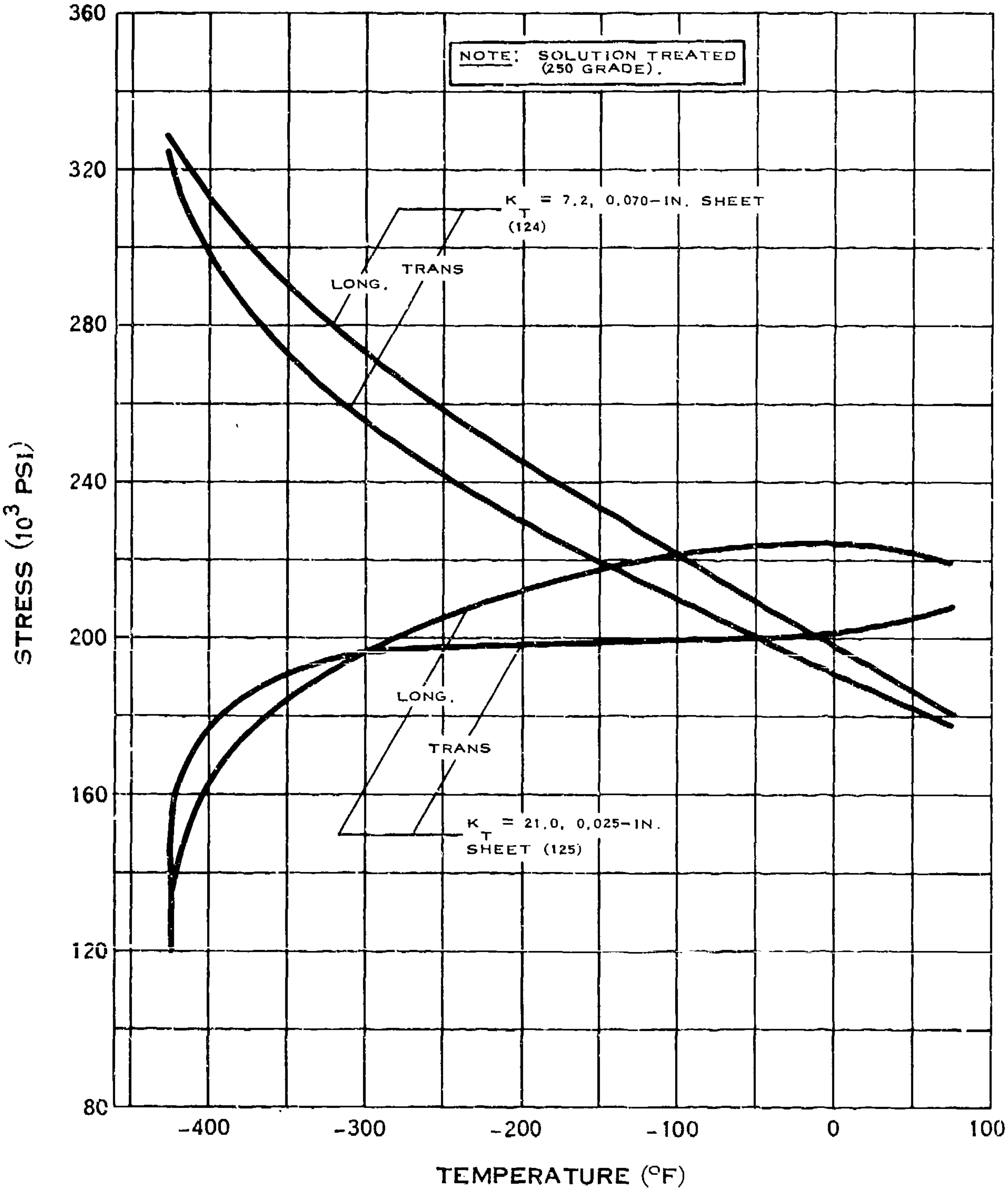
ELONGATION OF 18% Ni MARAGING STEEL

(7-65)

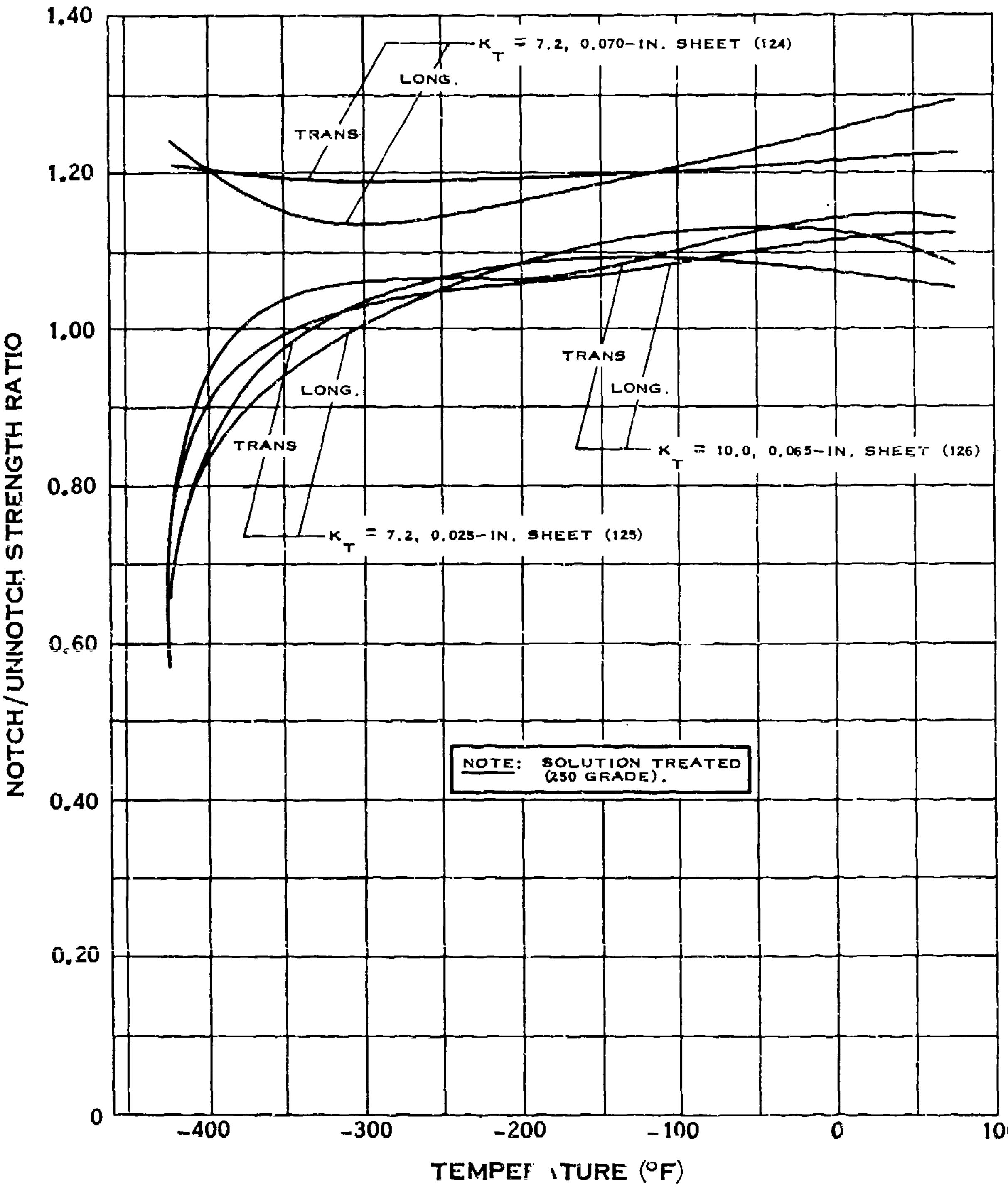


ELONGATION OF 18% Ni MARAGING STEEL

(7-63)

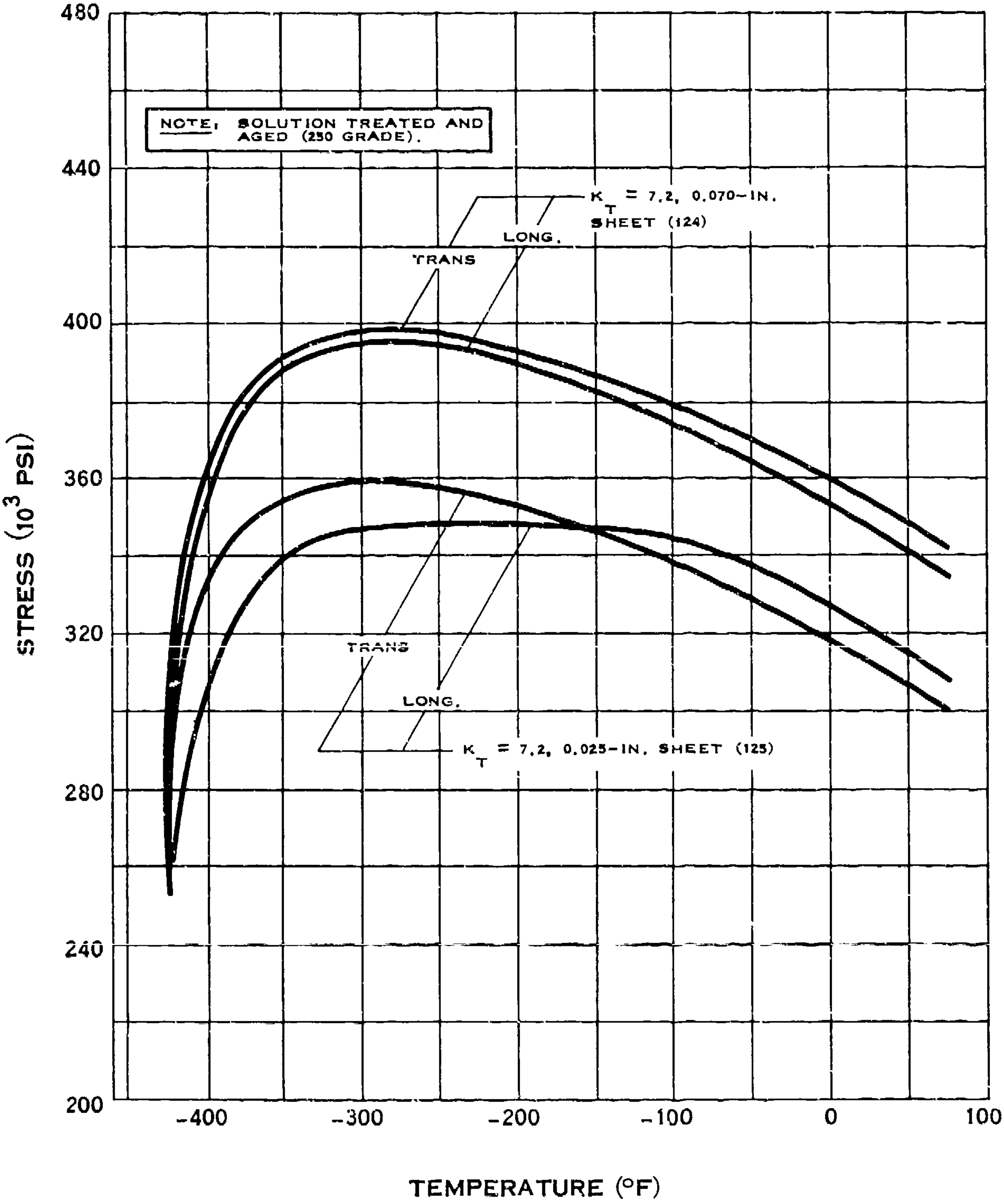


NOTCH TENSILE STRENGTH OF 18% Ni MARAGING STEEL

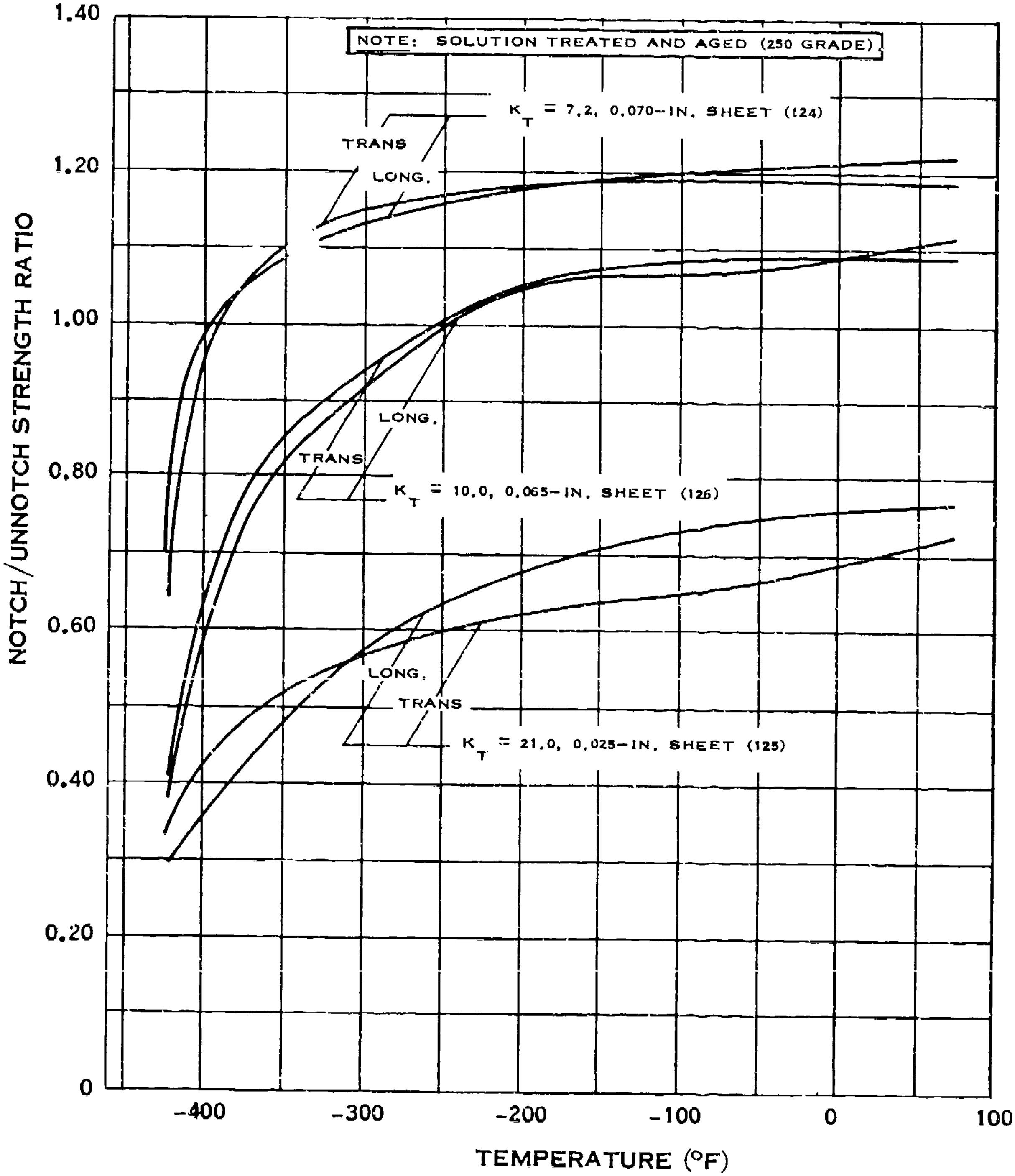


NOTCH STRENGTH RATIO OF 18% Ni MARAGING STEEL

(7-65)

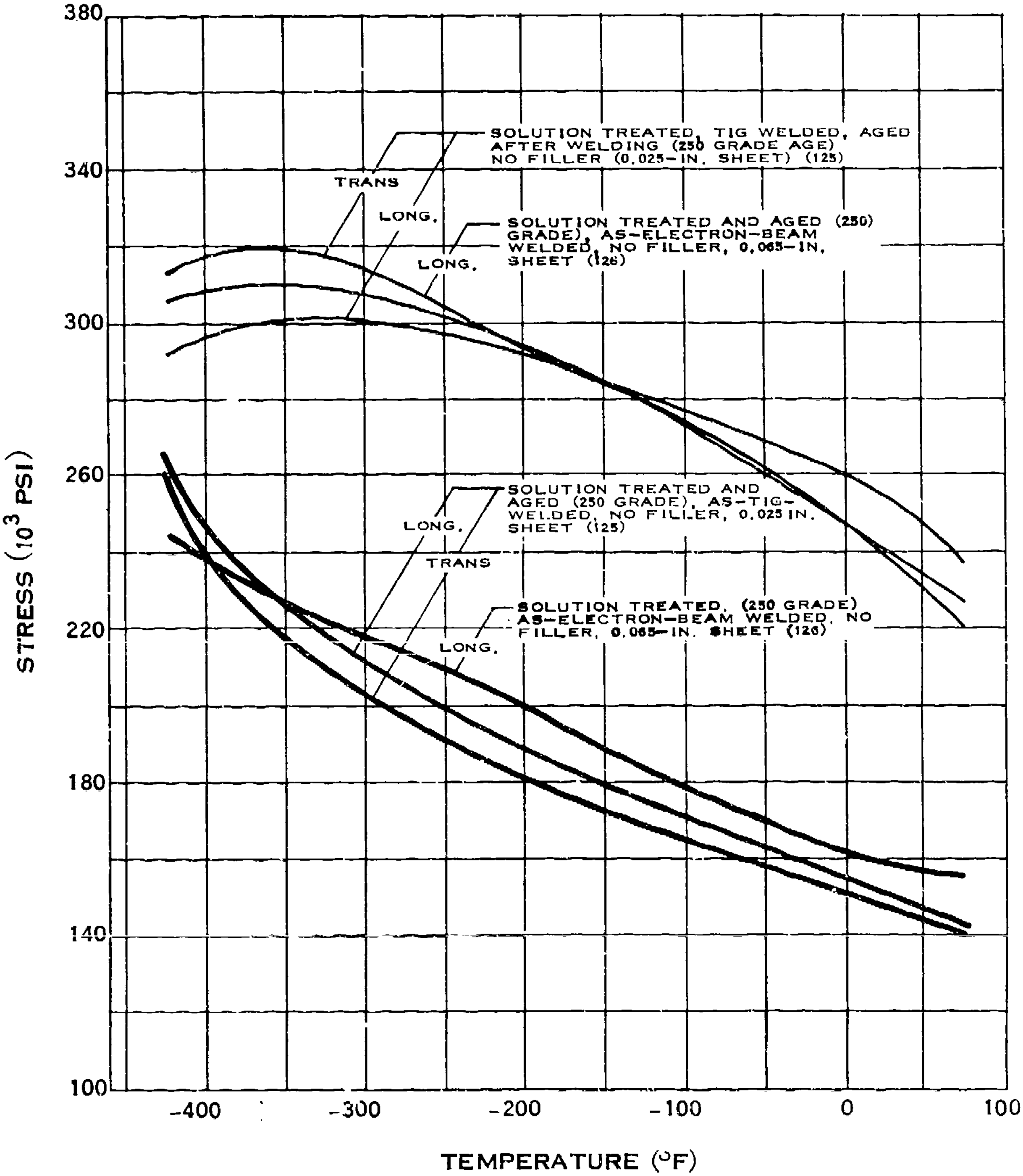


NOTCH TENSILE STRENGTH OF 18% Ni MARAGING STEEL



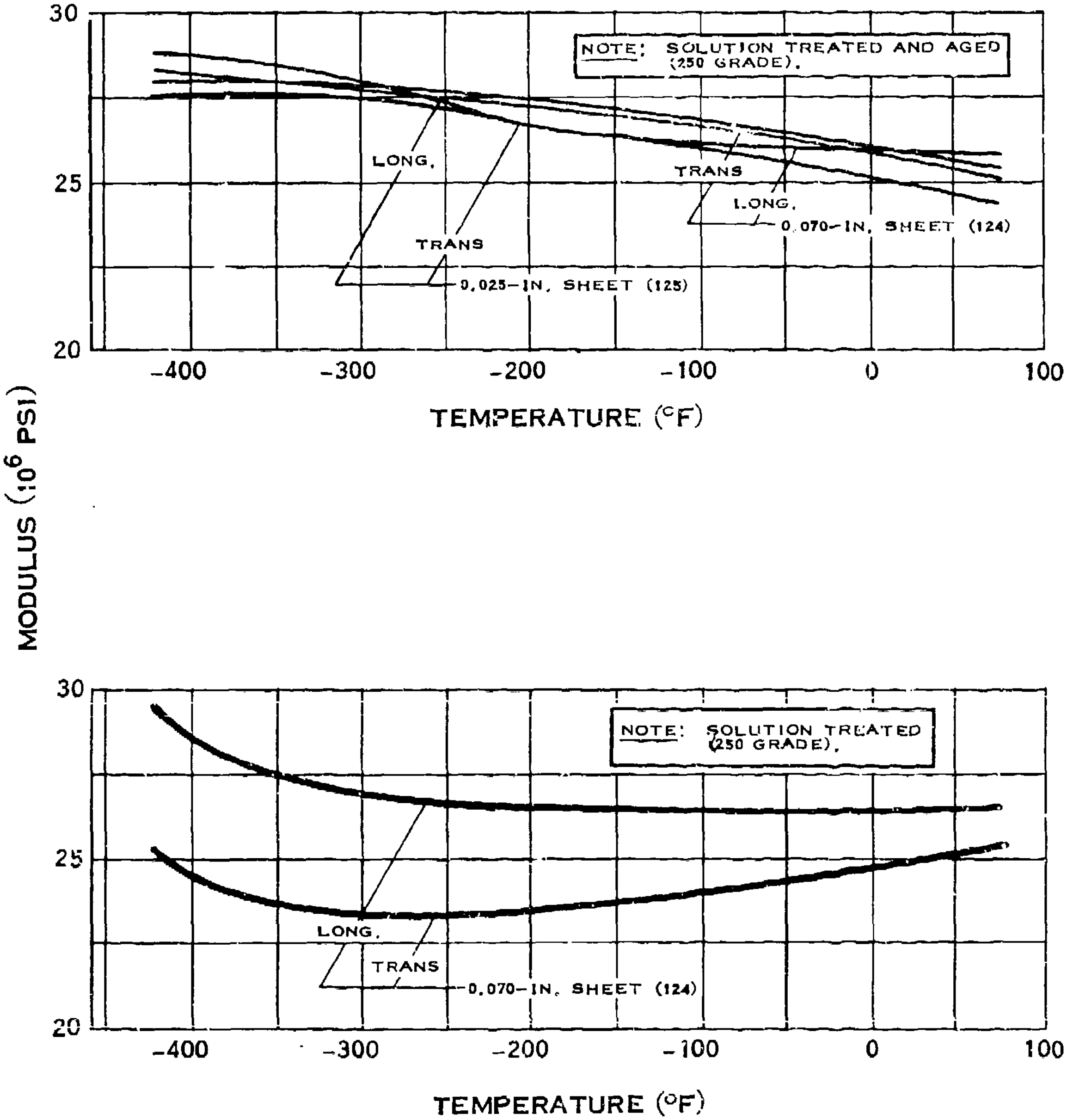
NOTCH STRENGTH RATIO OF 18% Ni MARAGING STEEL

E.5.g



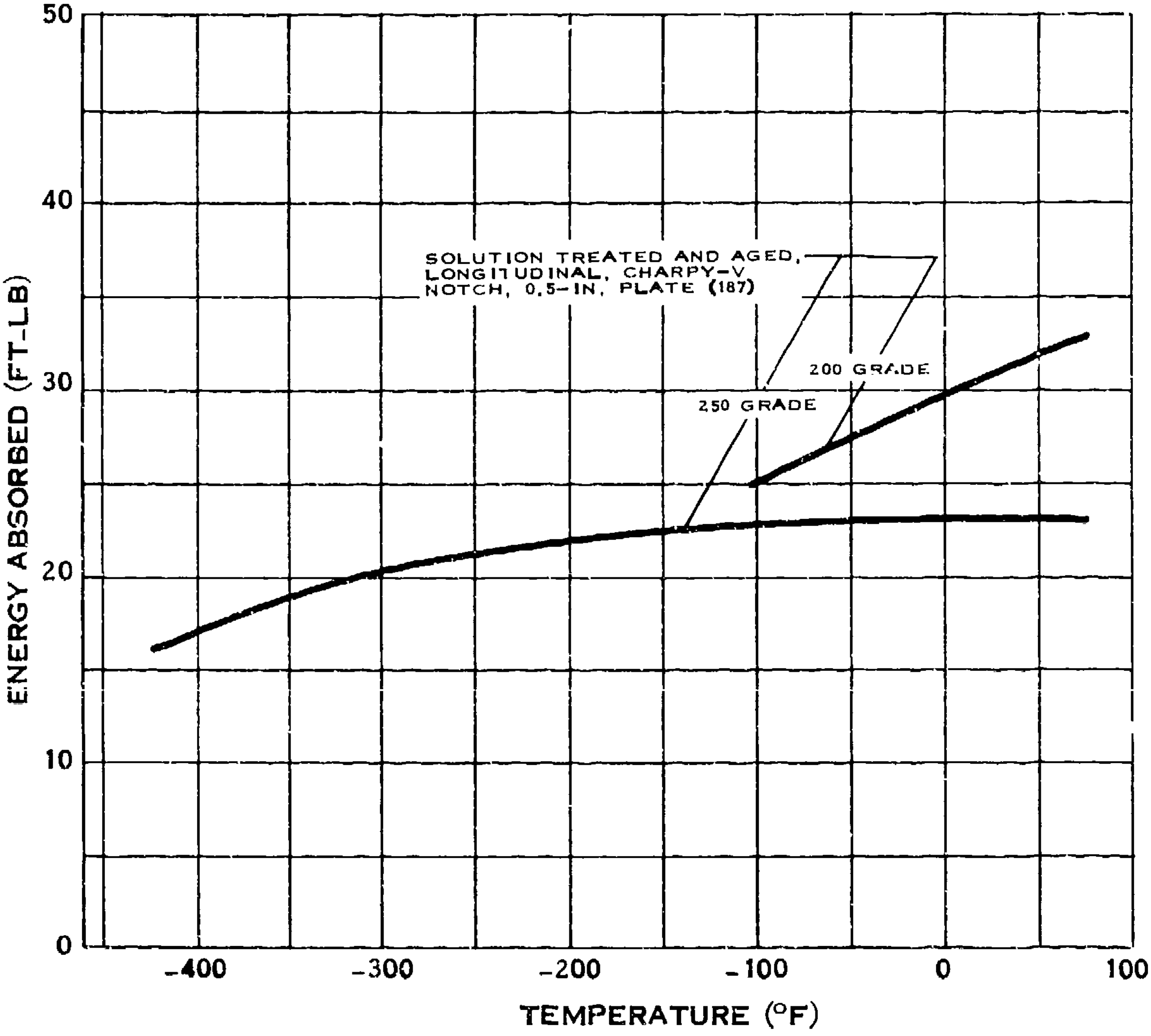
WELD TENSILE STRENGTH OF 18% Ni MARAGING STEEL

E.5.i



MODULUS OF ELASTICITY OF 18% Ni MARAGING STEEL

E.5.j

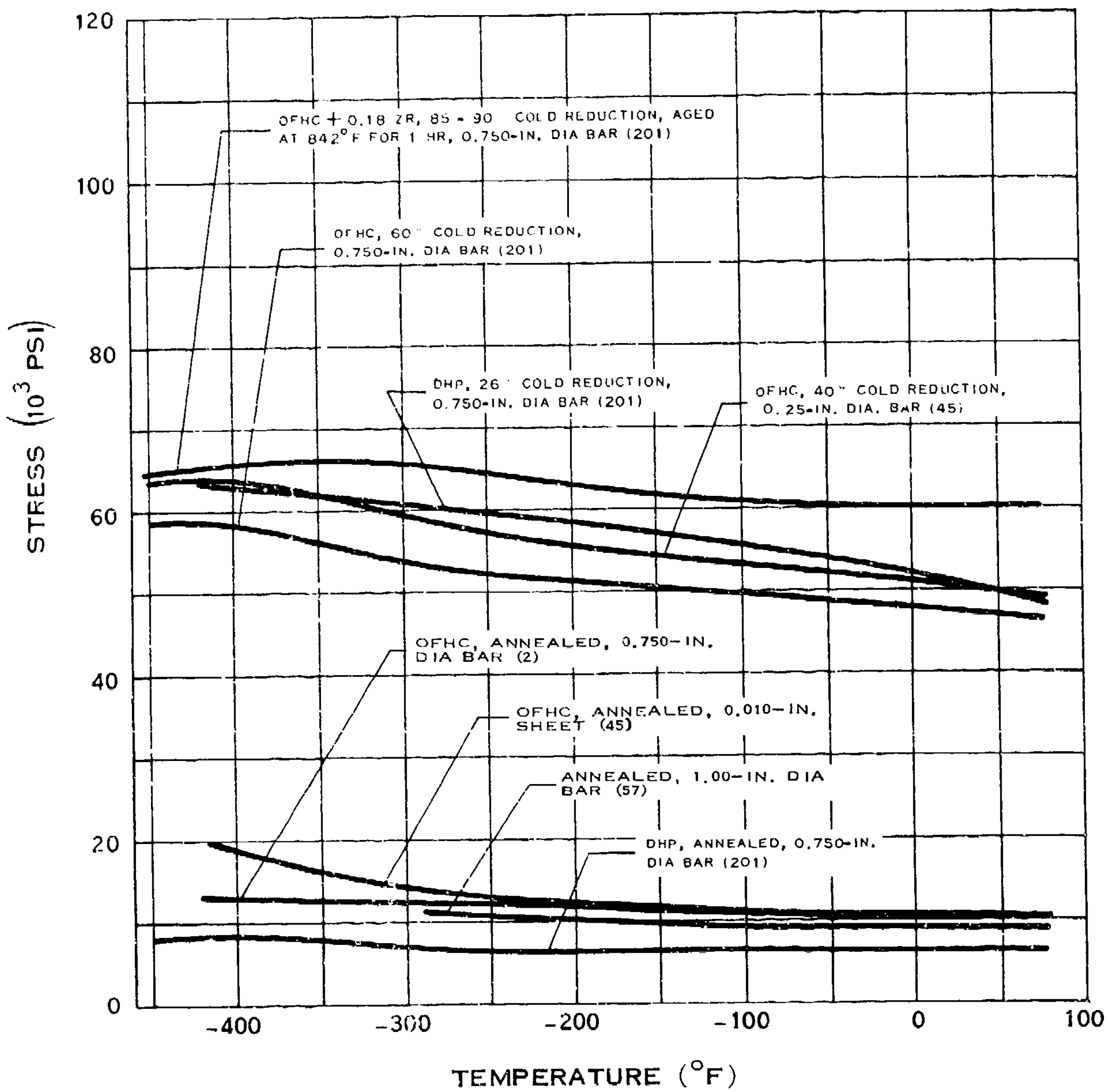


IMPACT STRENGTH OF 18% Ni MARAGING STEEL

(3-66)

F - MISCELLANEOUS METALS AND ALLOYS

F.1.a



YIELD STRENGTH OF COPPER

(6-68)

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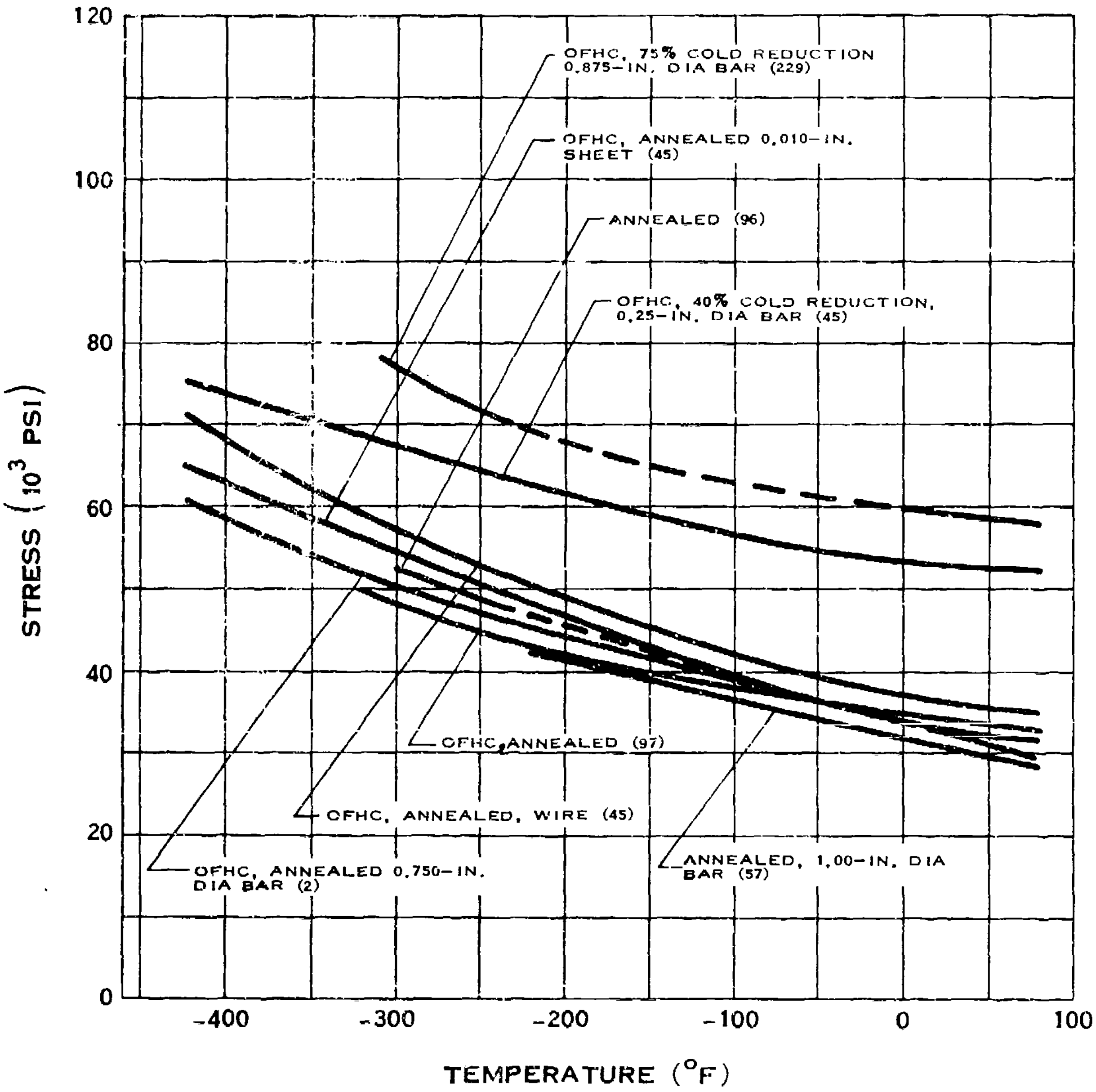
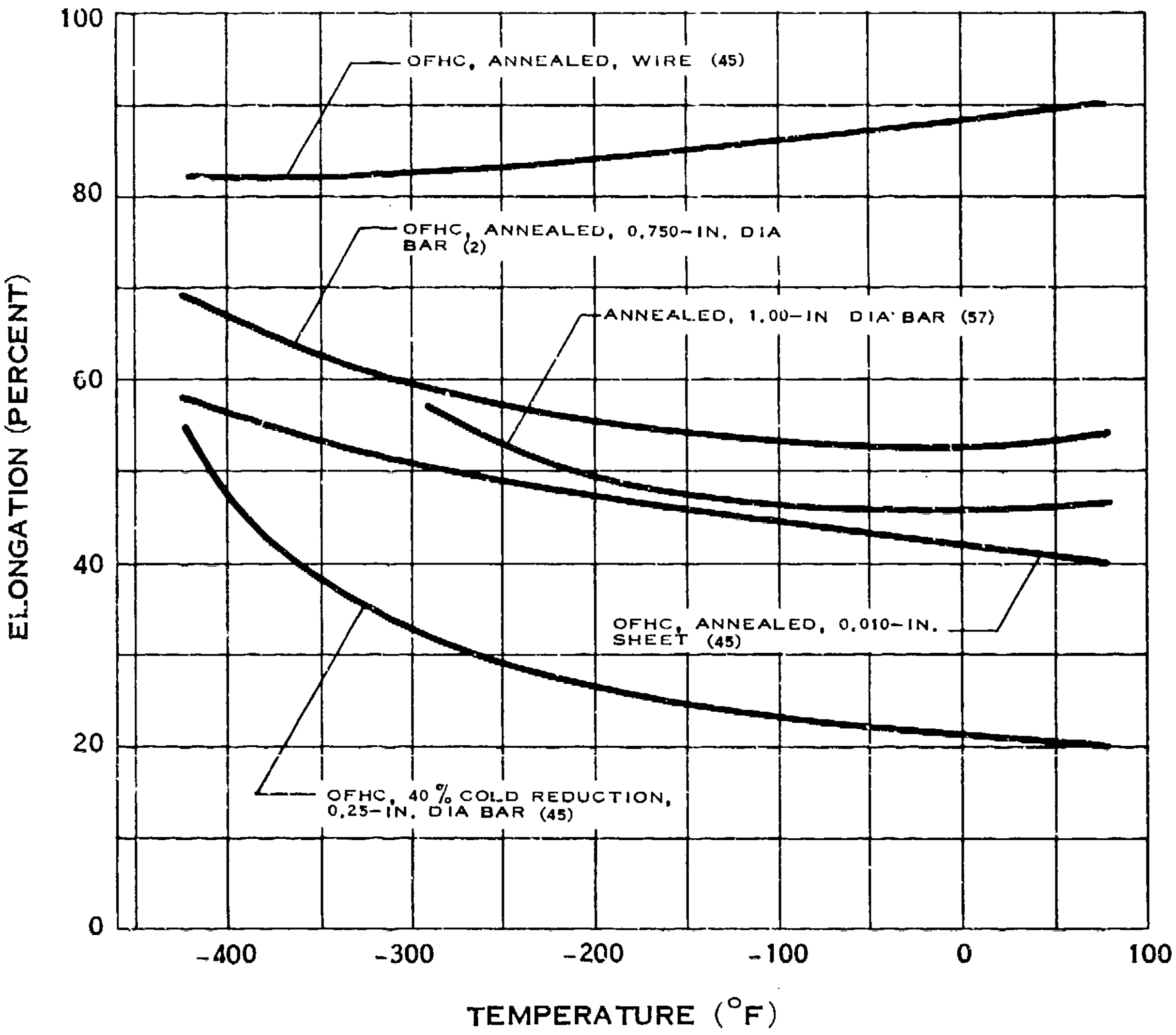
F.1.b



TENSILE STRENG:H OF COPPER

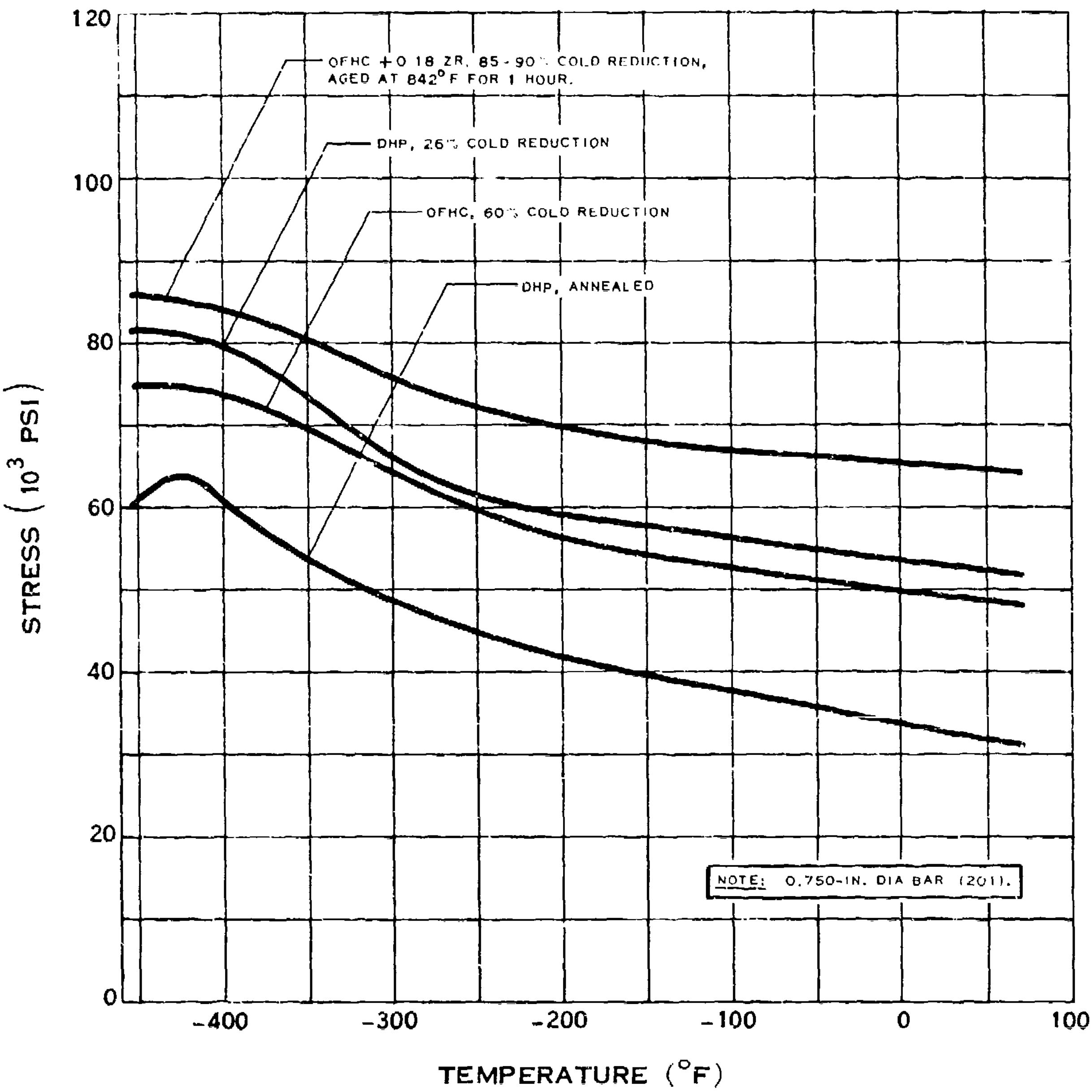
(7–64)



ELONGATION OF COPPER

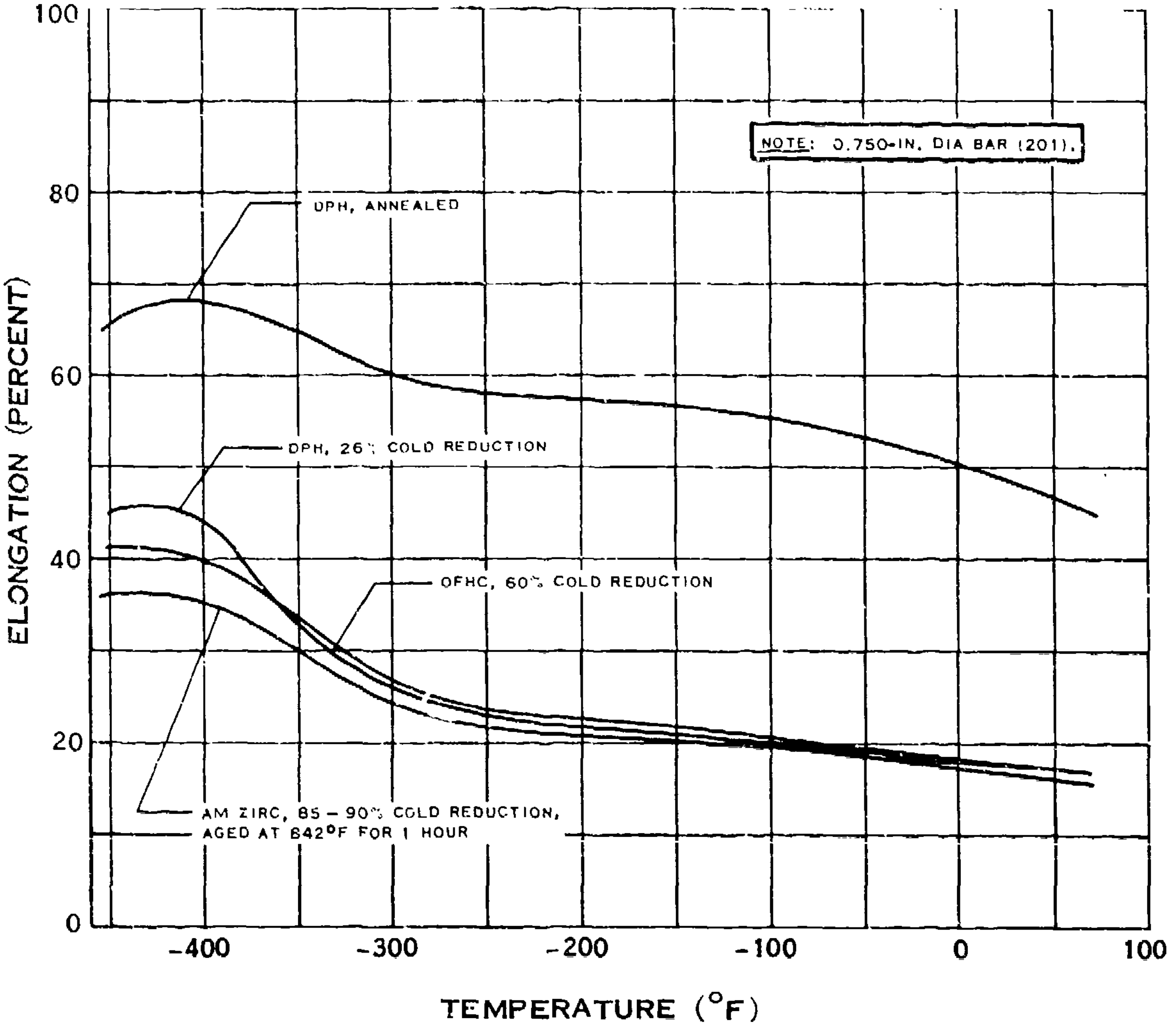
(7-64)

F.1.b-1



TENSILE STRENGTH OF COPPER

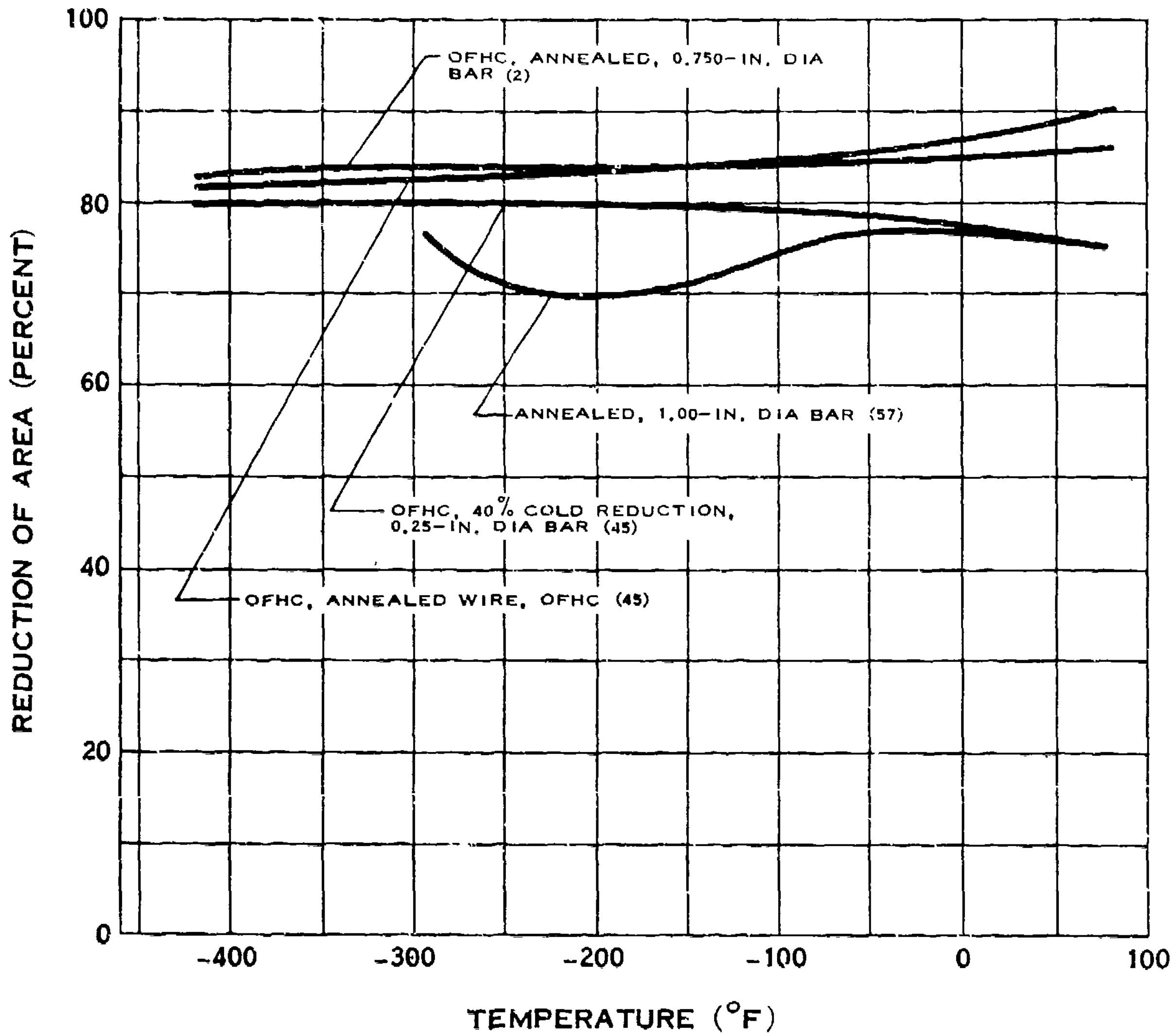
(6-68)



ELONGATION OF COPPER

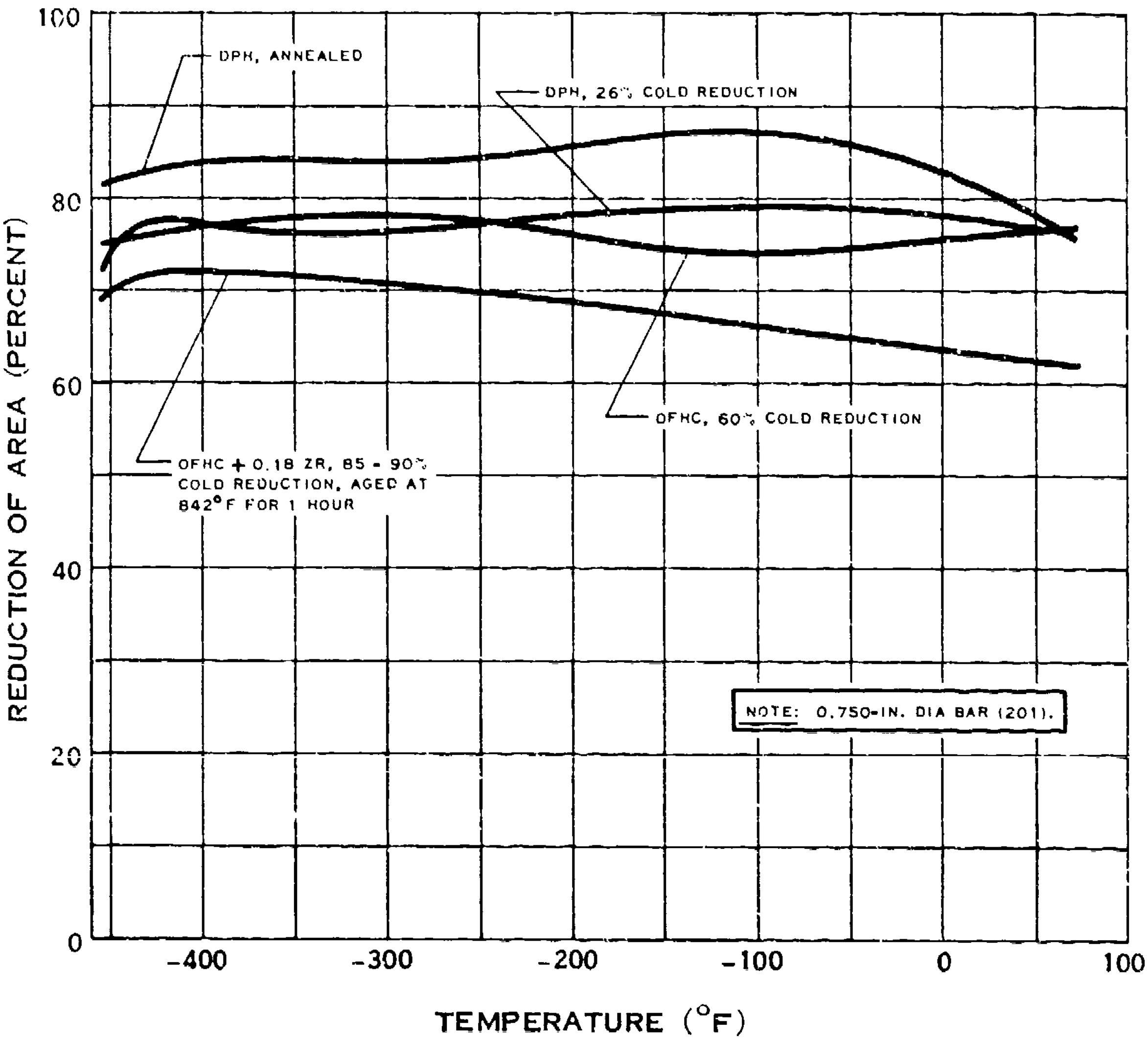
(6-68)

F.1.d



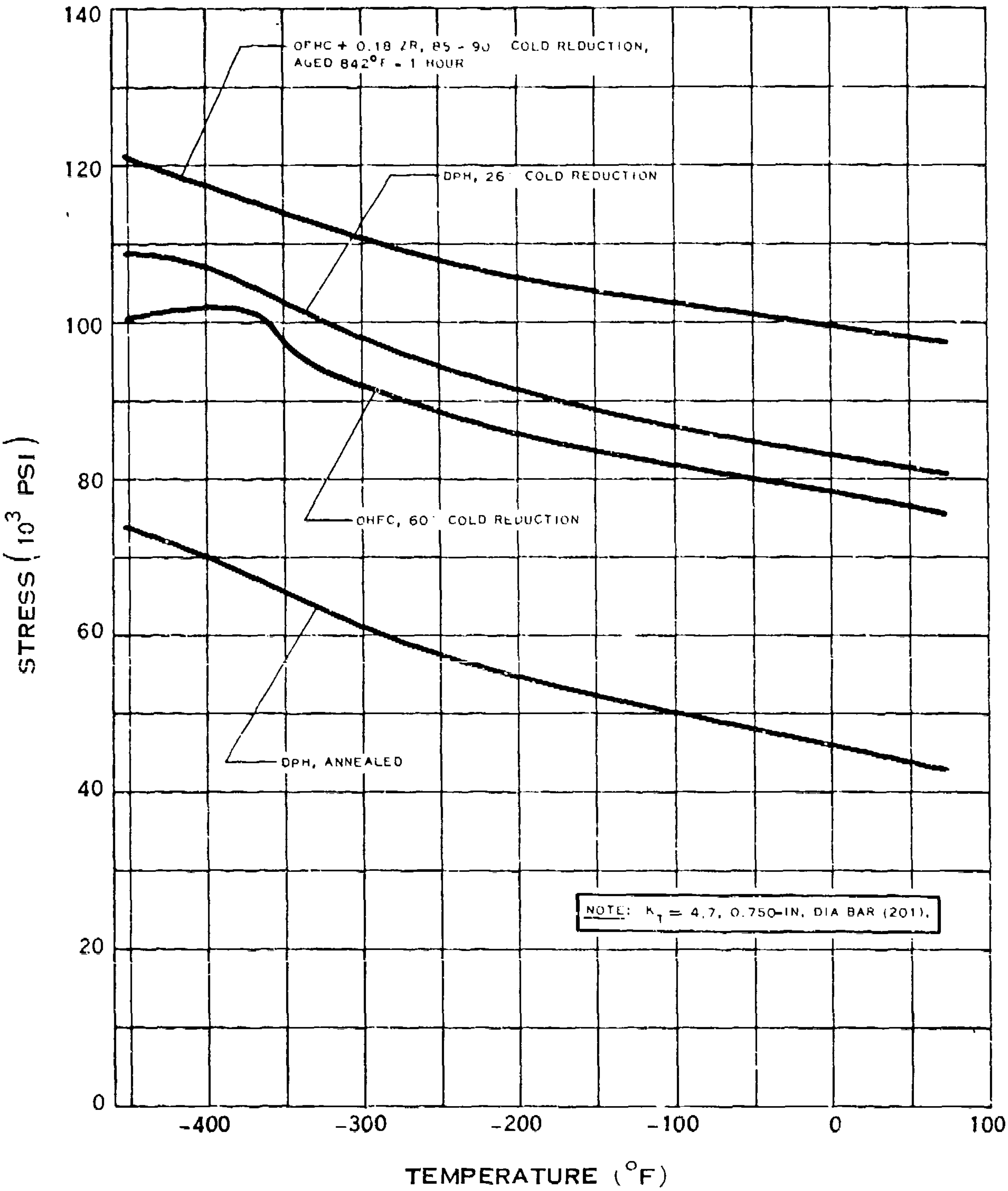
REDUCTION OF AREA OF COPPER

(7-64)



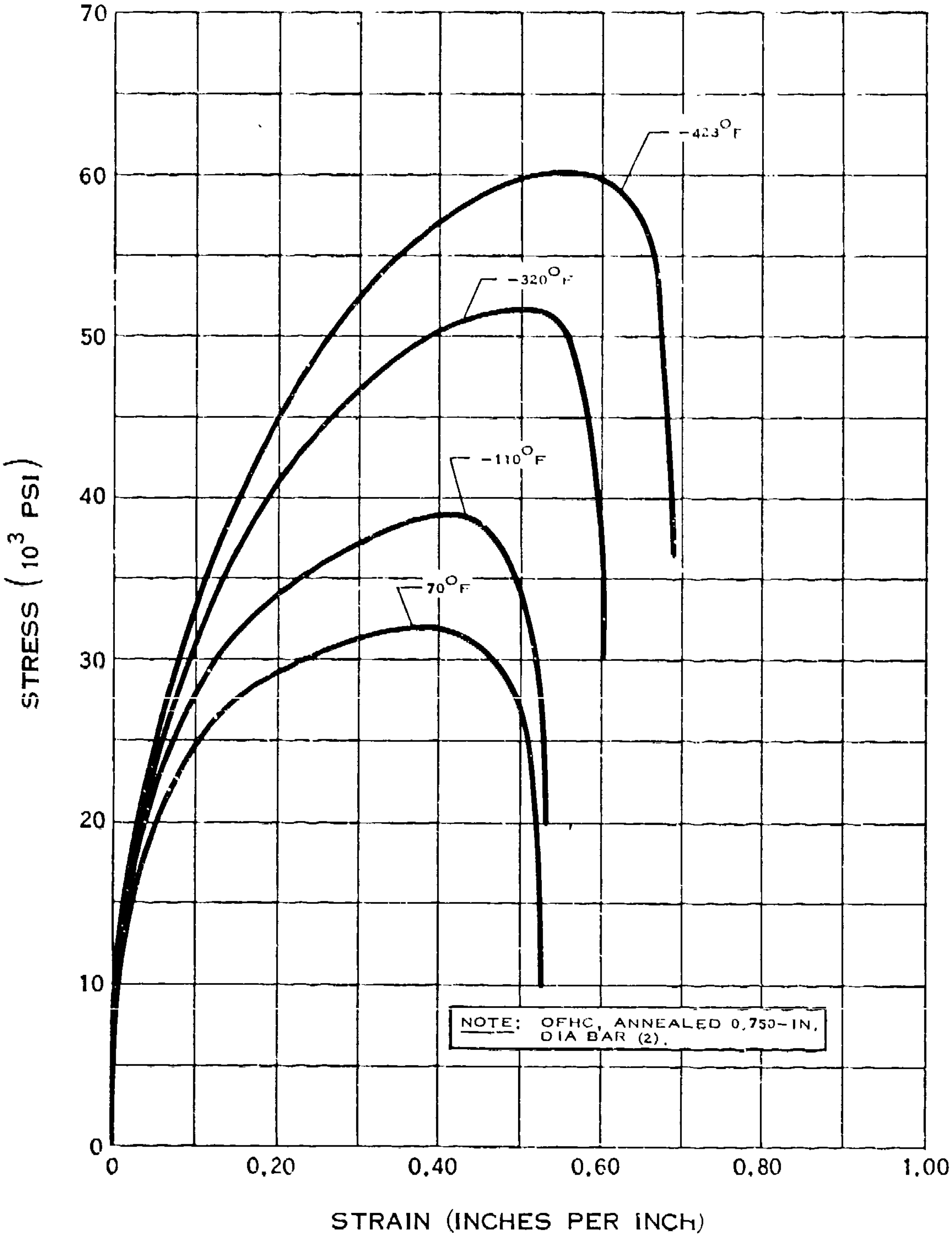
REDUCTION OF AREA OF COPPER

(6-68)



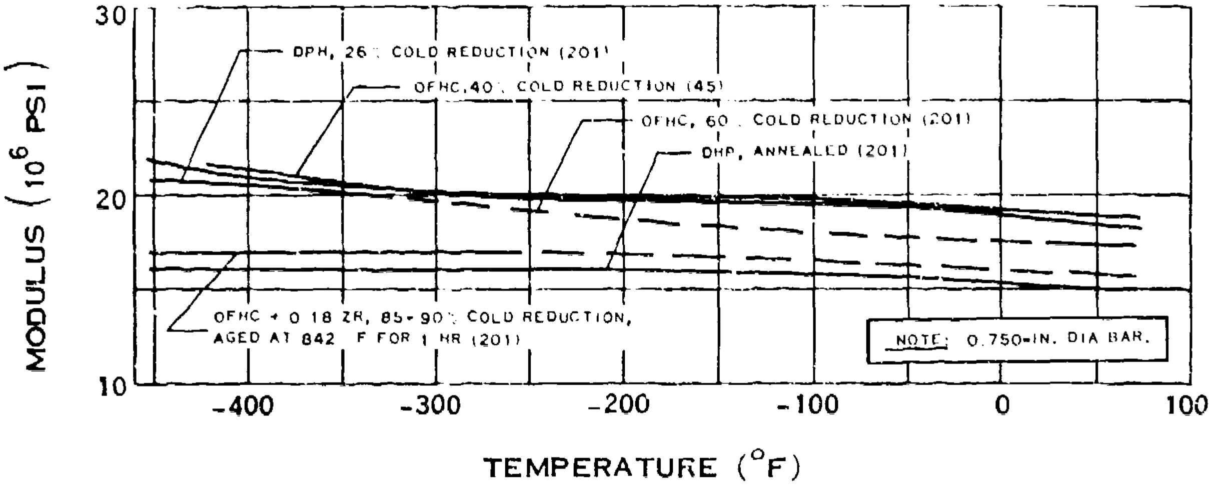
NOTCH TENSILE STRENGTH OF COPPER

(6-68)

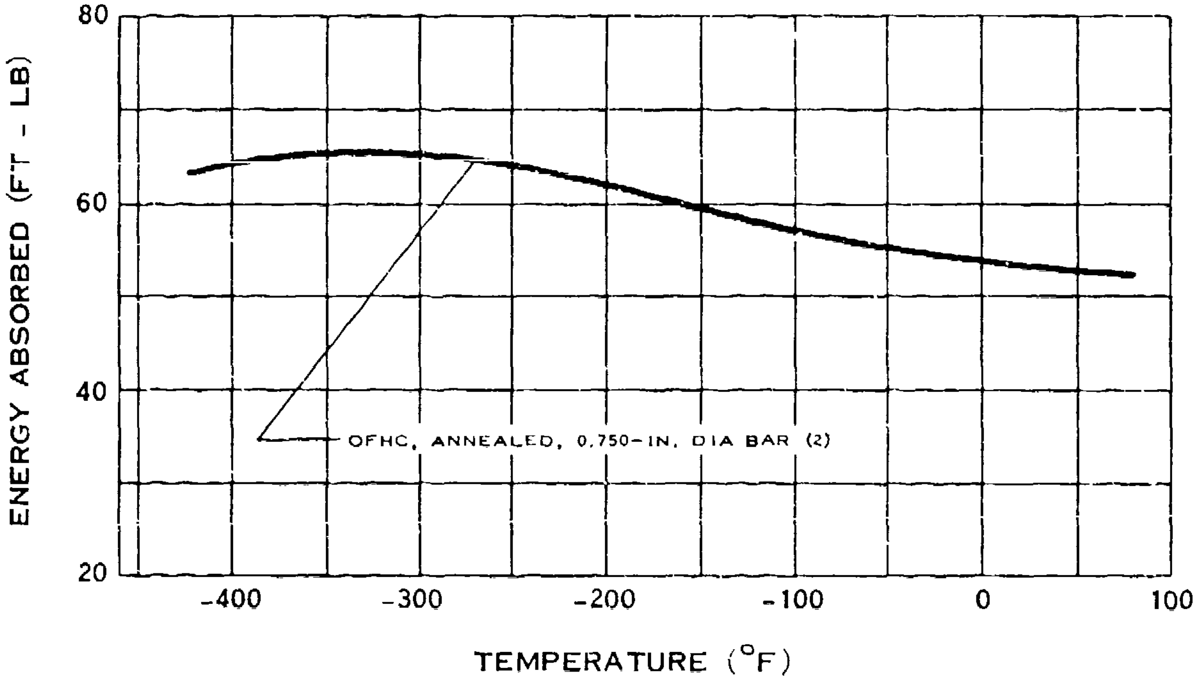


STRESS-STRAIN DIAGRAM FOR COPPER

(7-64)



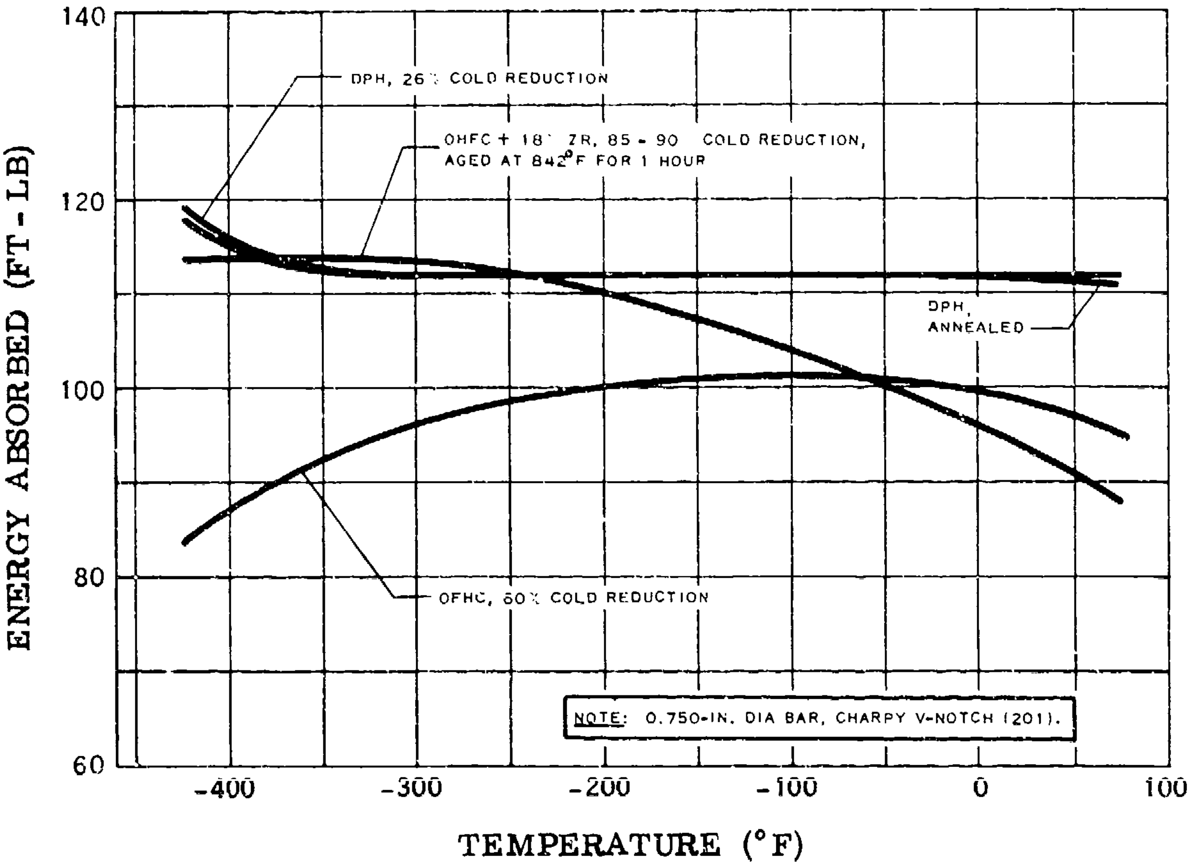
MODULUS OF ELASTICITY OF COPPER



IMPACT STRENGTH OF COPPER

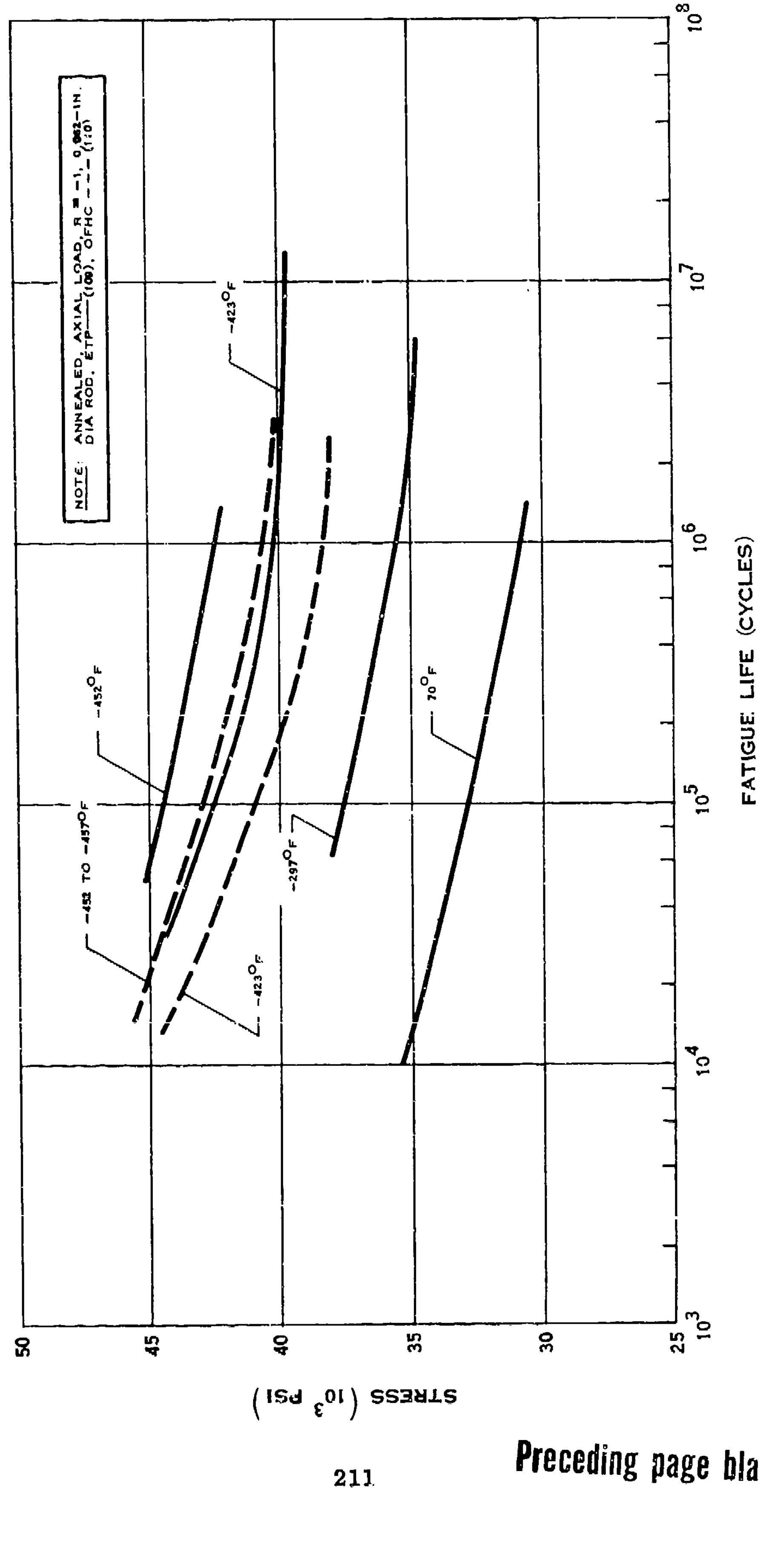
(6-68)

F.1.j-1



IMPACT STRENGTH OF COPPER

(6-68)



FATIGUE STRENGTH OF COPPER

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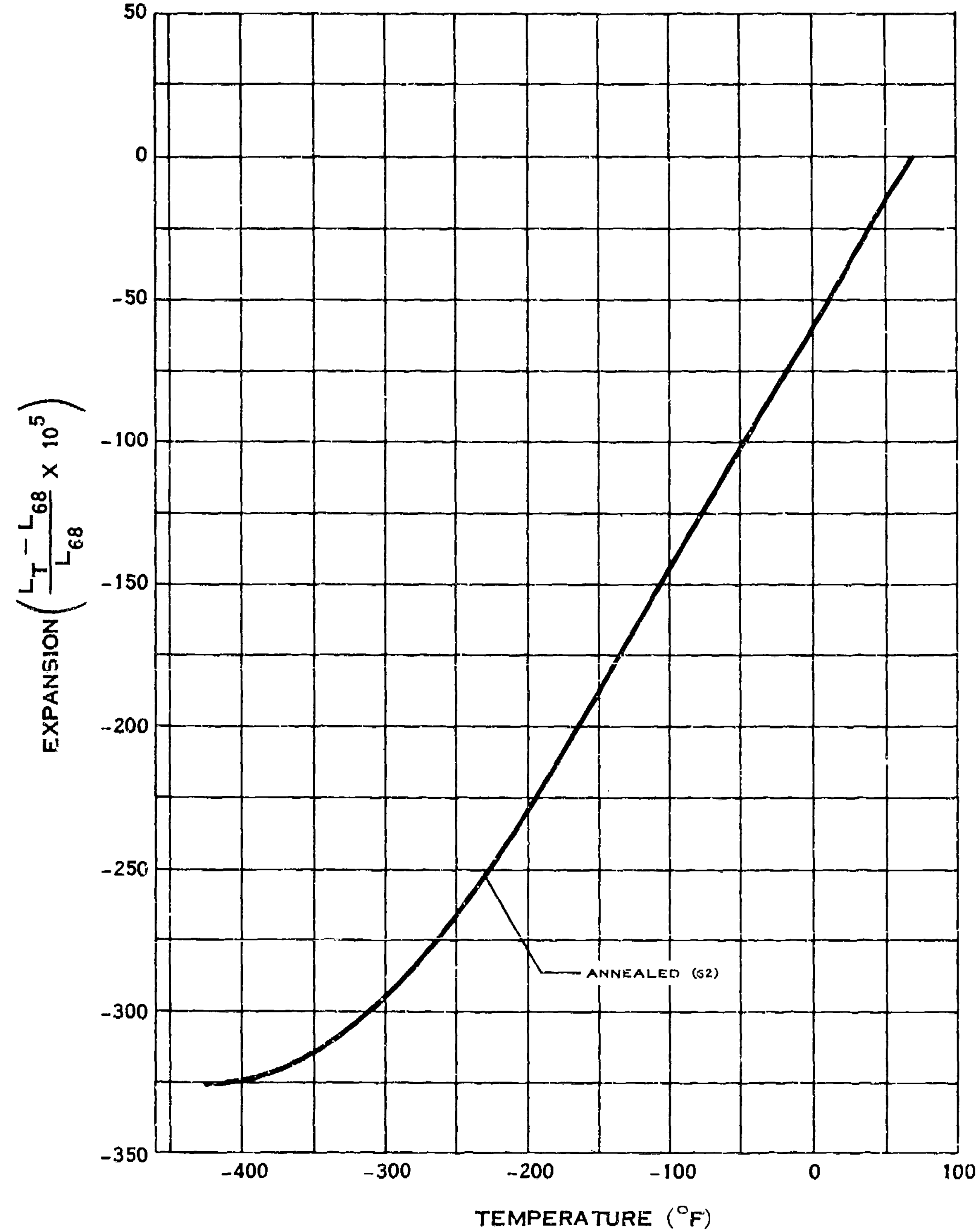
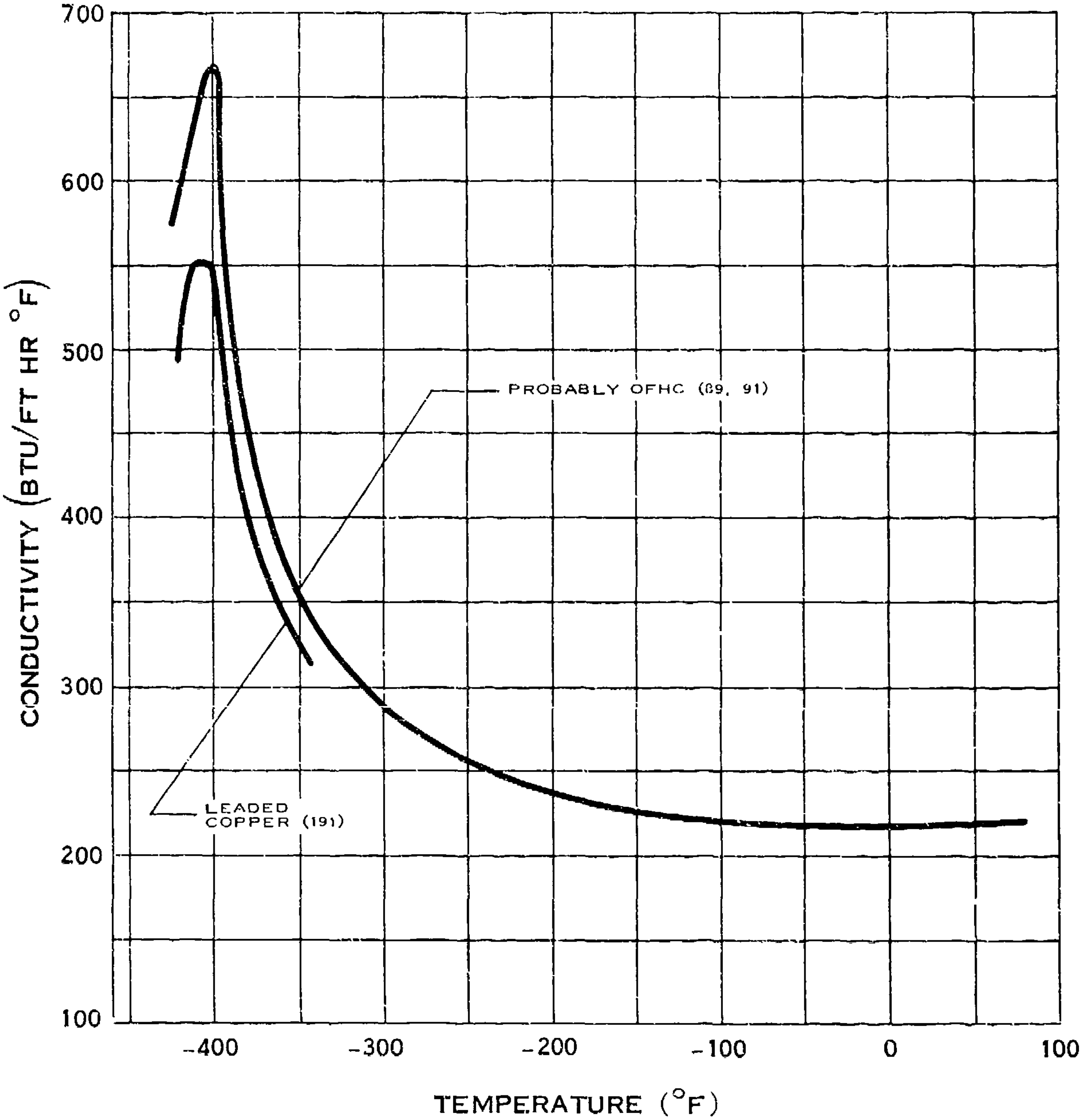


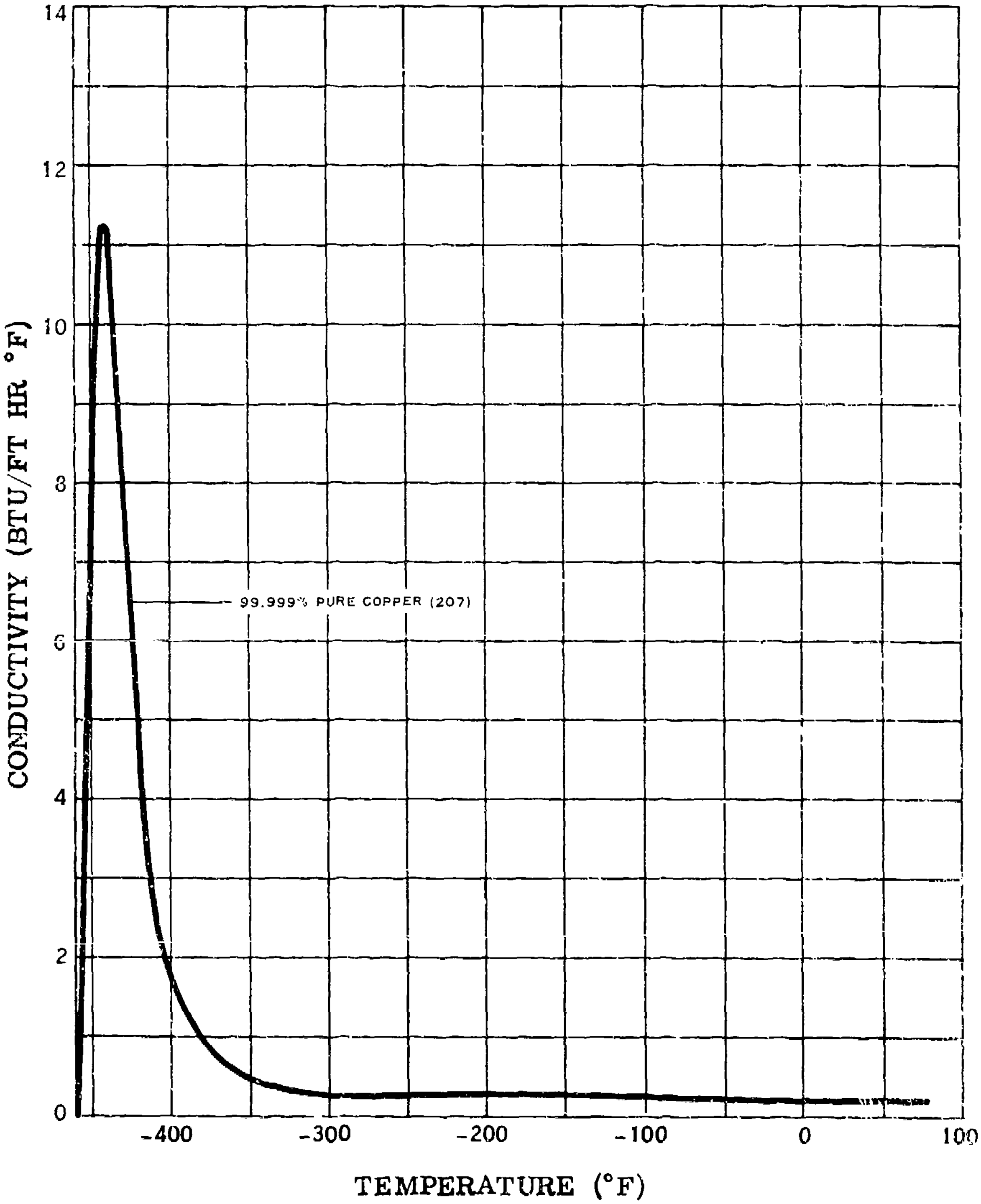
THERMAL EXPANSION OF COPPER

(7-64)



THERMAL CONDUCTIVITY OF COPPER

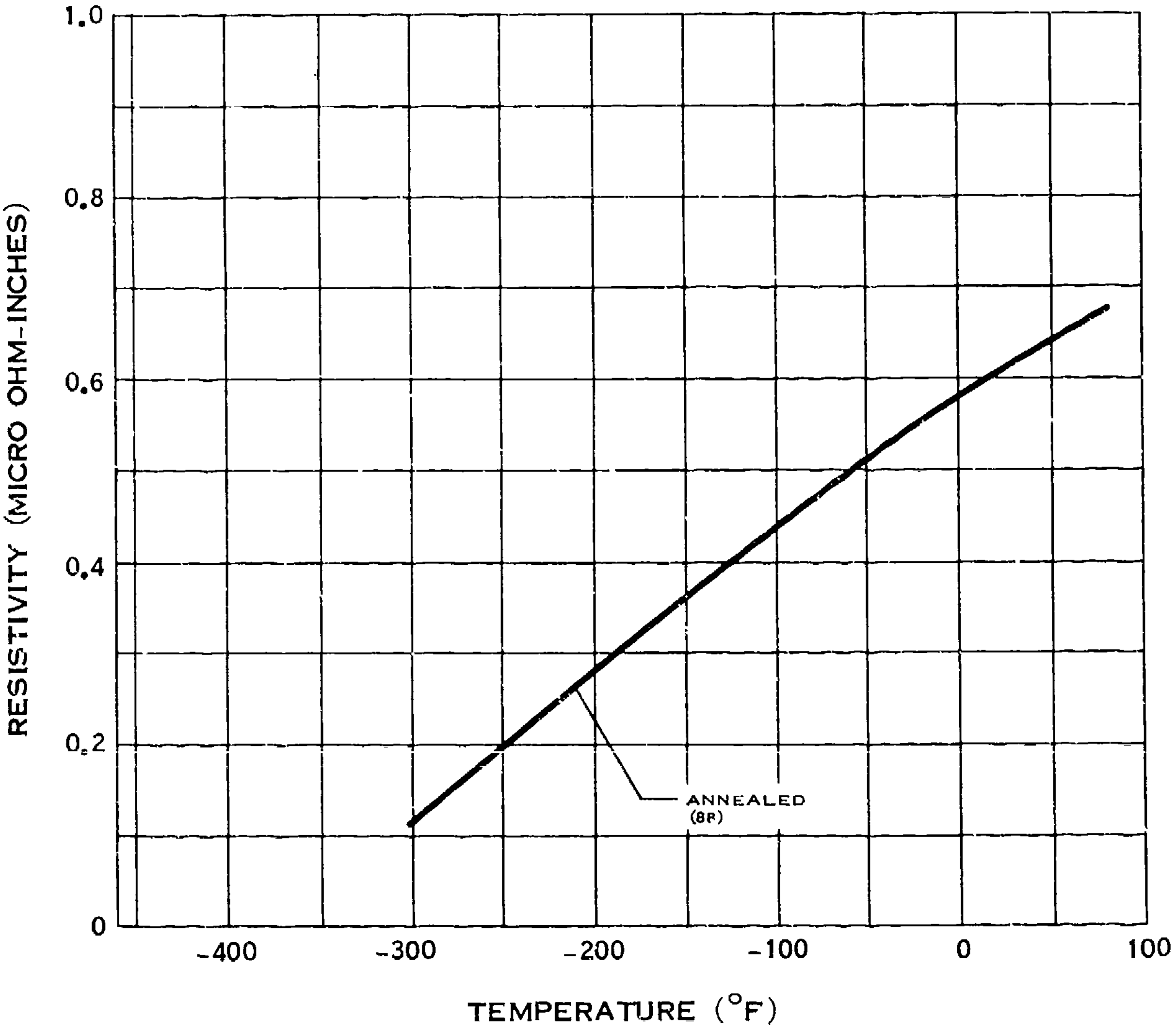
(3–66)



THERMAL CONDUCTIVITY OF COPPER

(6-68)

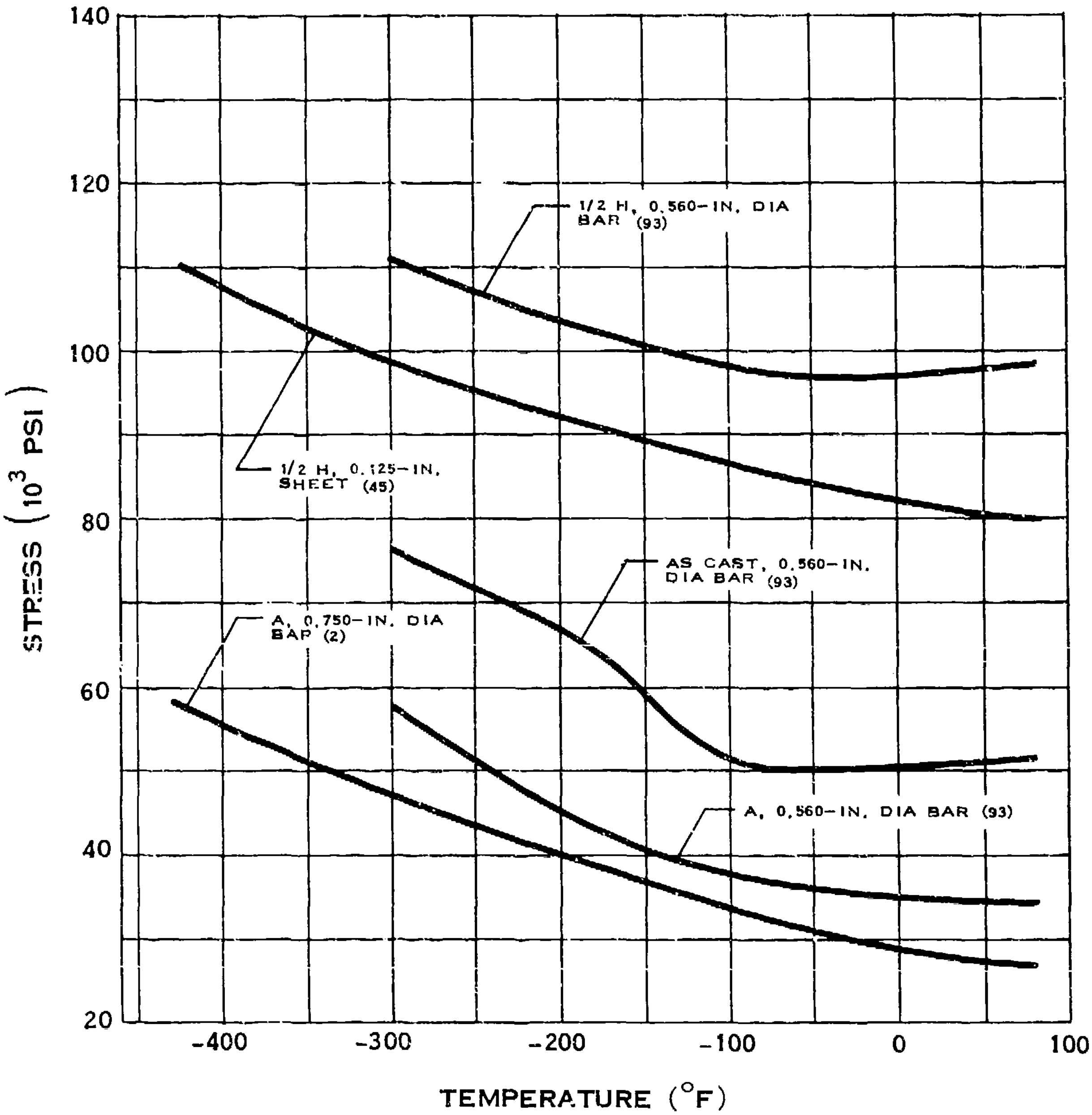
F.1.w



ELECTRICAL RESISTIVITY OF COPPER

(7-64)

F.2.a



YIELD STRENGTH OF BERYLLIUM COPPER

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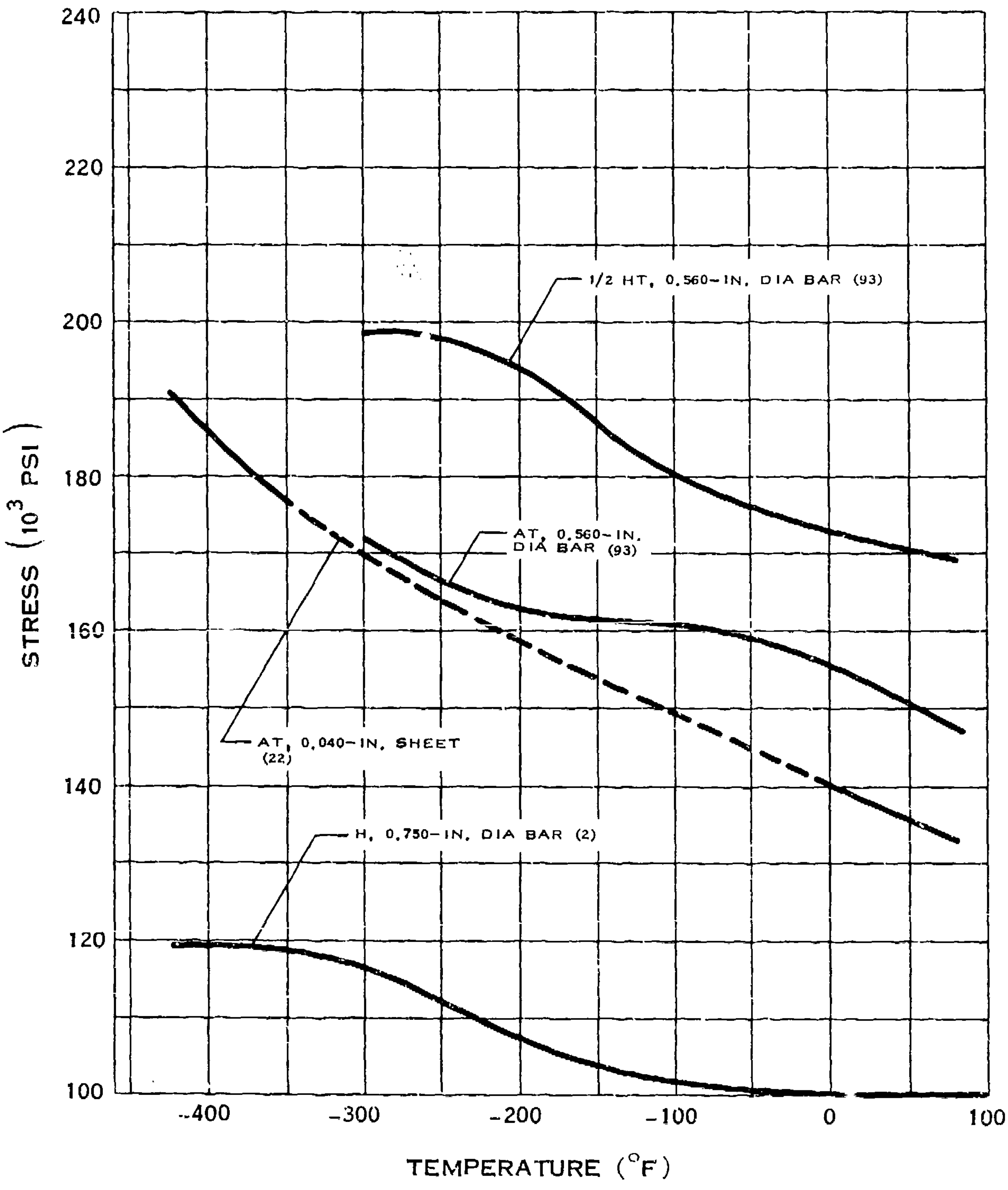
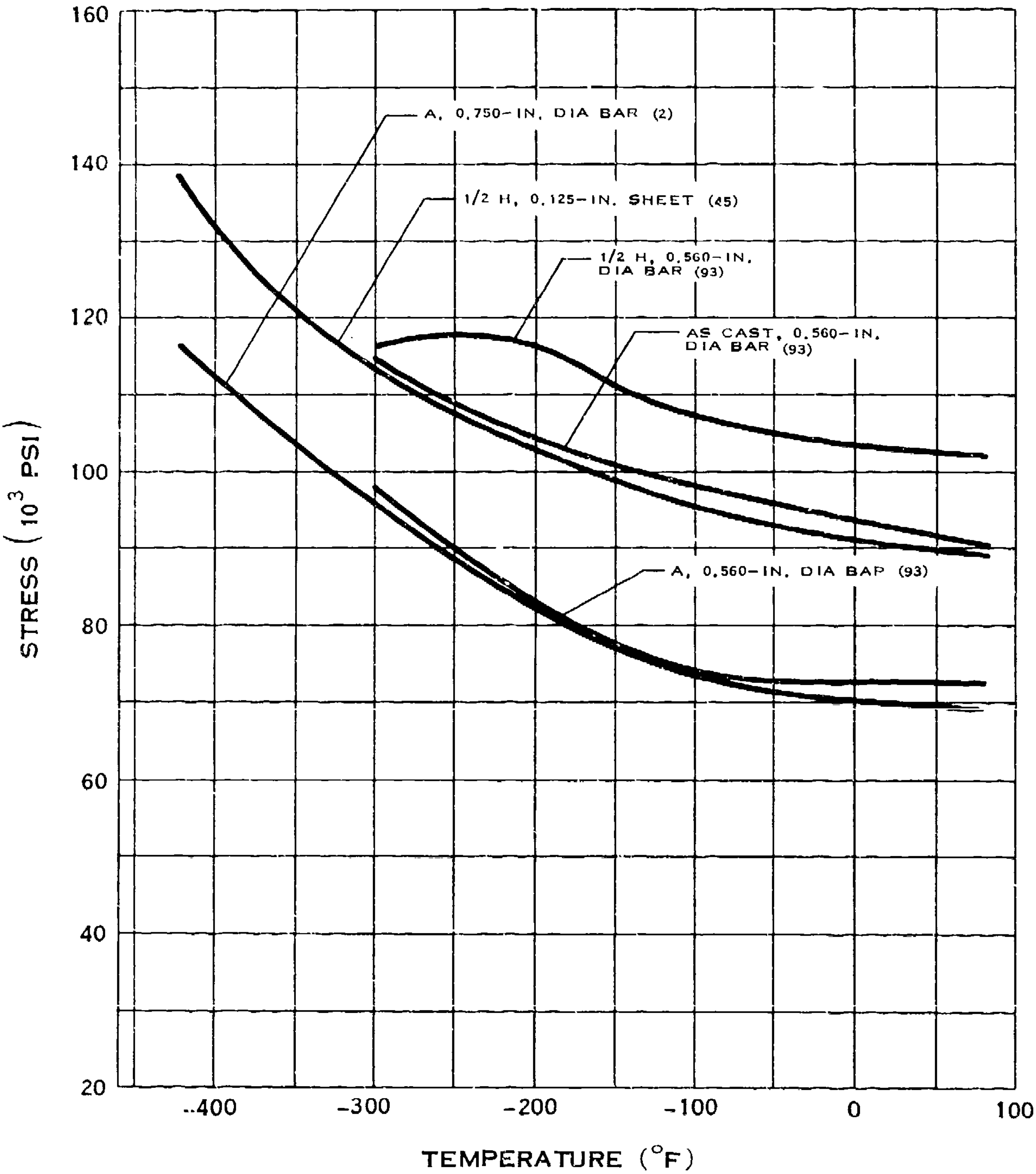
(7-64)

F.2.a-1



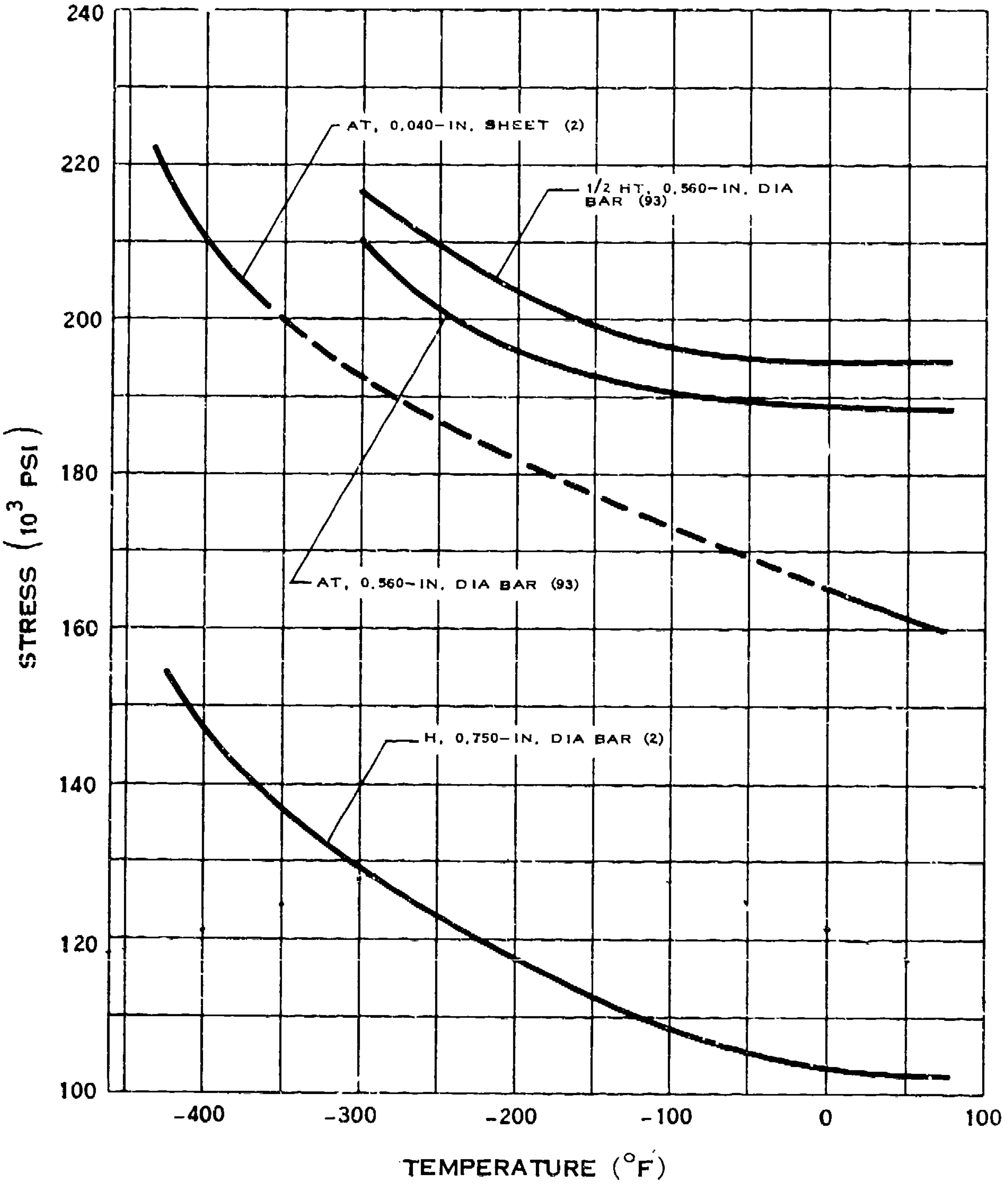
YIELD STRENGTH OF BERYLLIUM COPPER

(7-64)



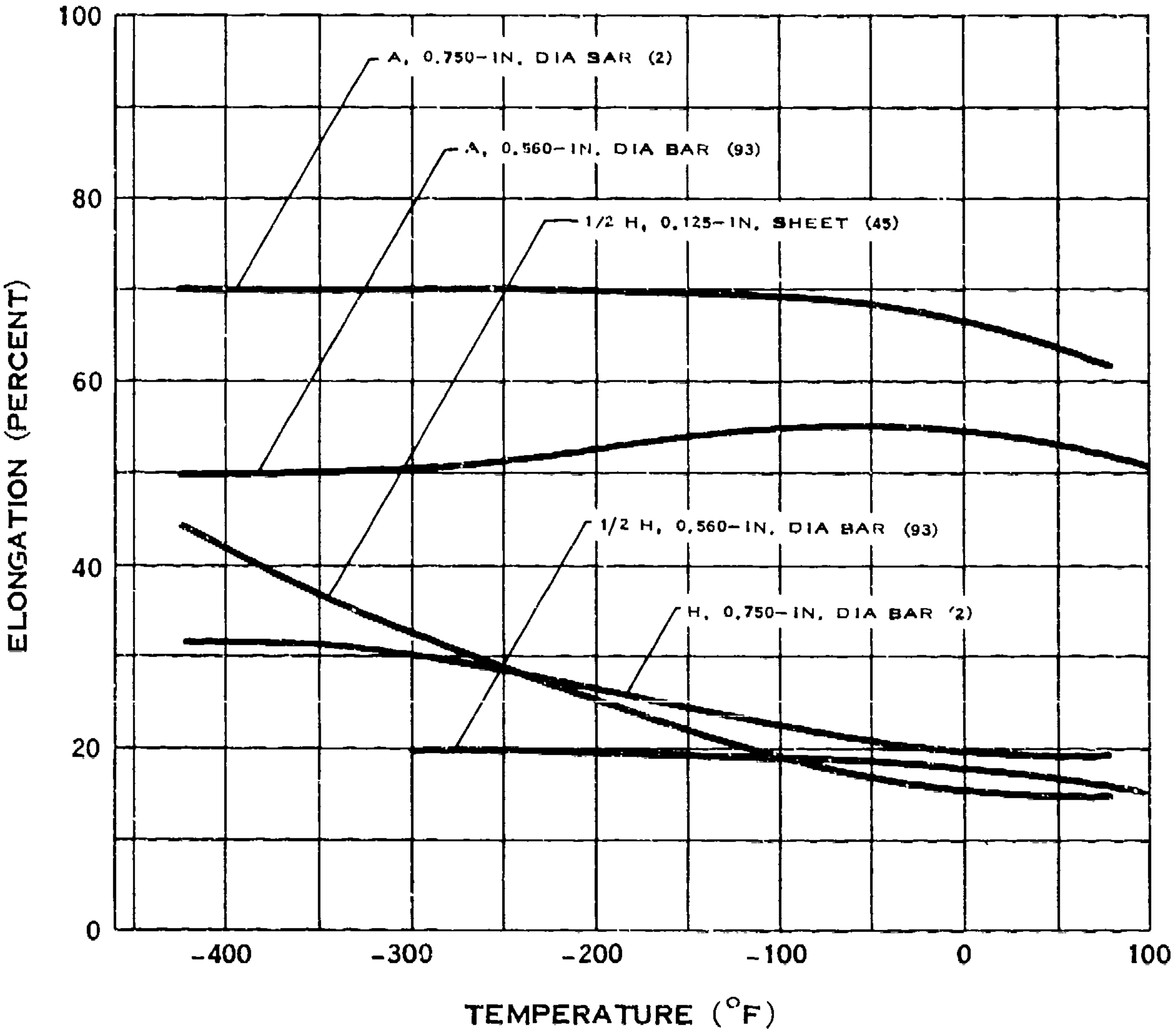
TENSILE STRENGTH OF BERYLLIUM COPPER

(7-64)



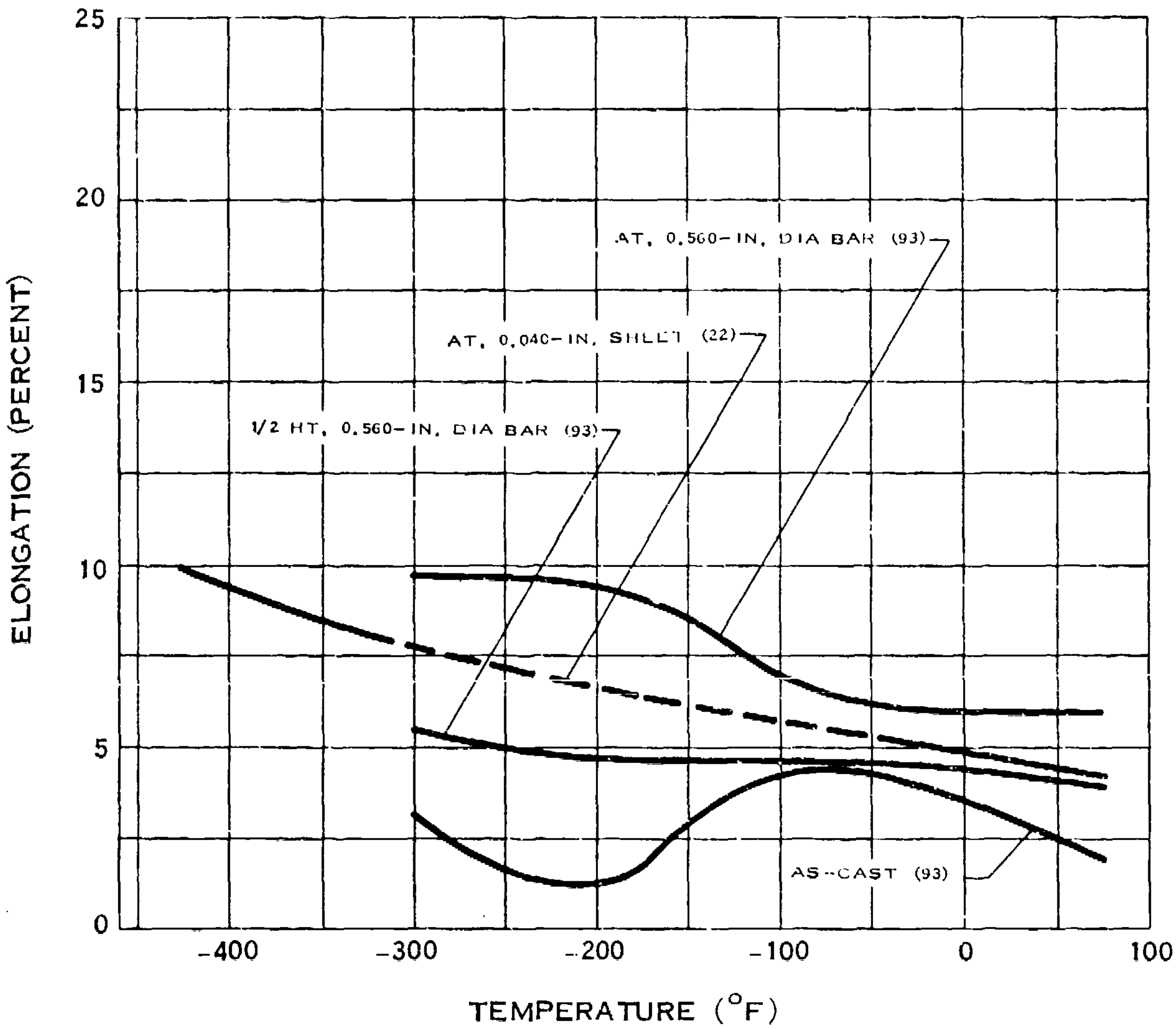
TENSILE STRENGTH OF BERYLLIUM COPPER

F.2.c



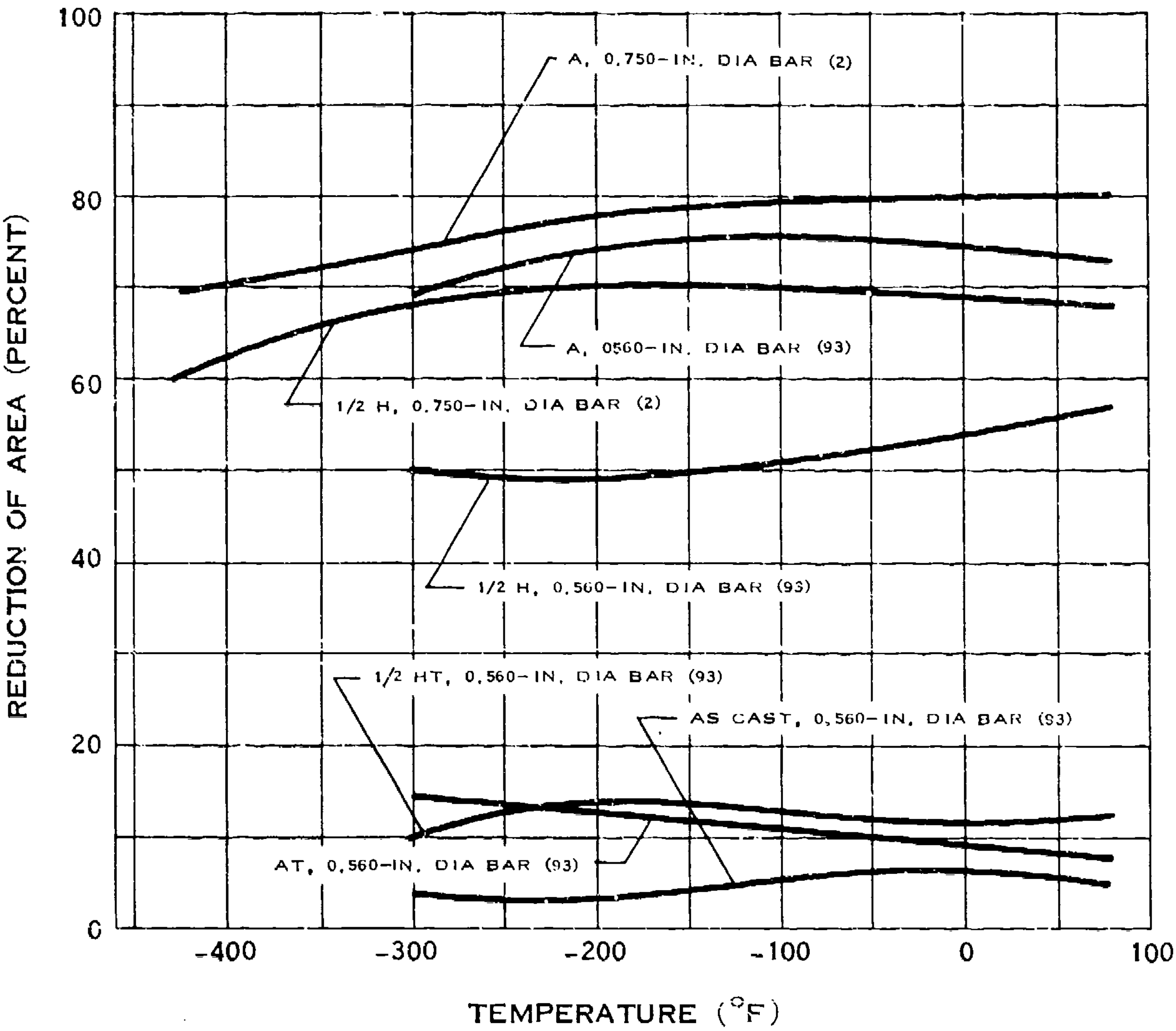
ELONGATION OF BERYLLIUM COPPER

F.2.c-1



ELONGATION OF BERYLLIUM COPPER

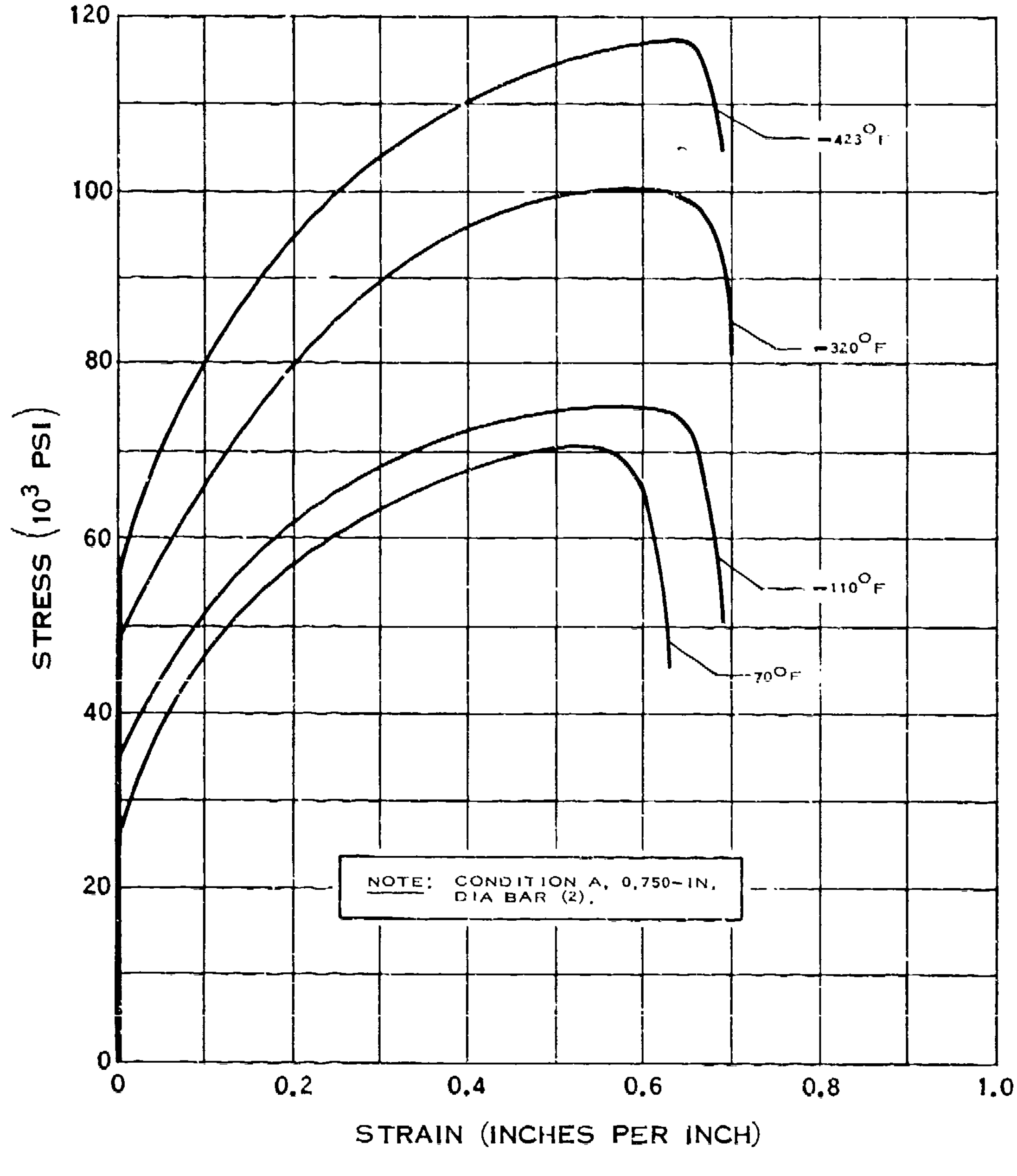
F.2.d



REDUCTION OF AREA OF BERYLLIUM COPPER

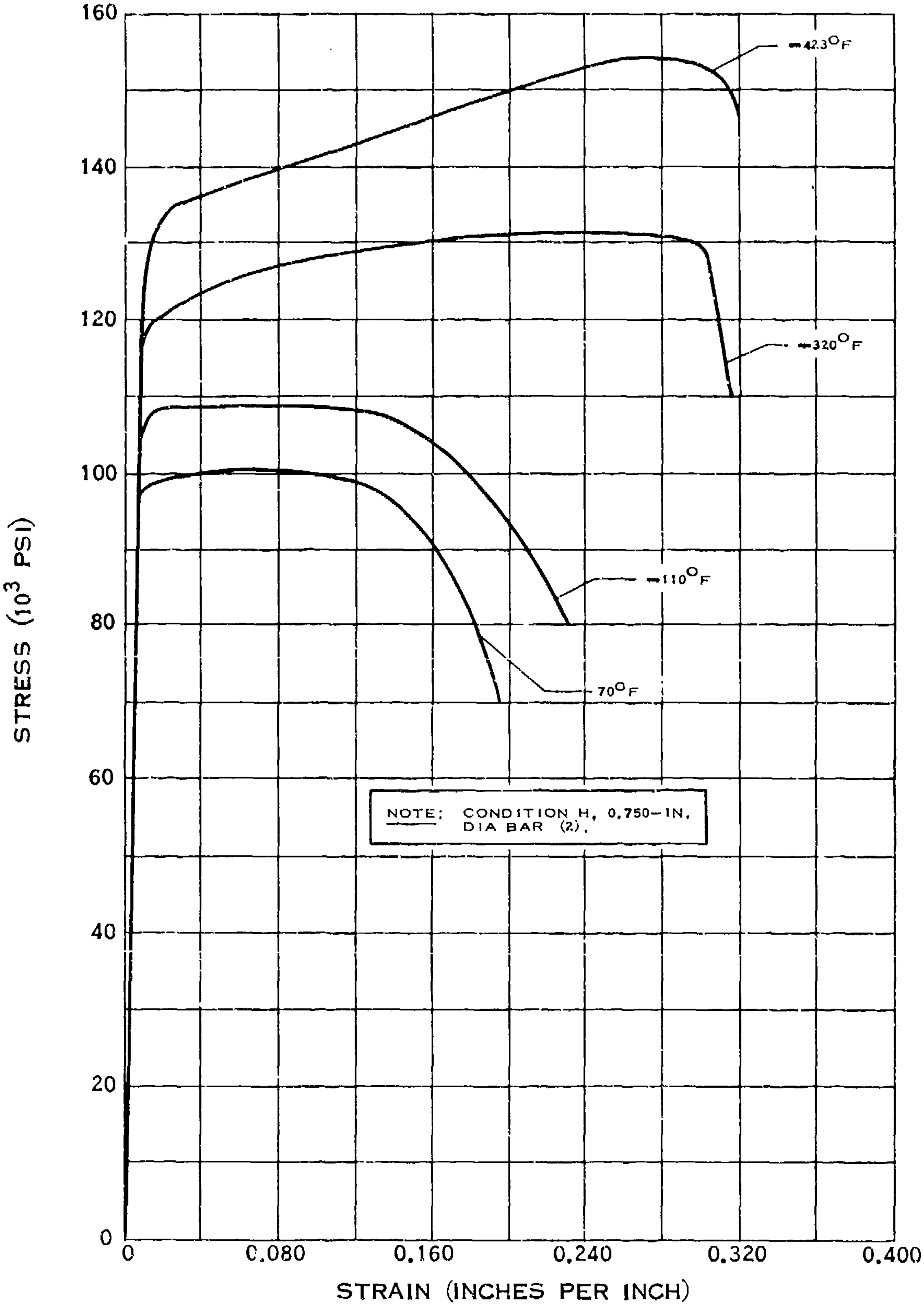
(7-64)

F.2-h



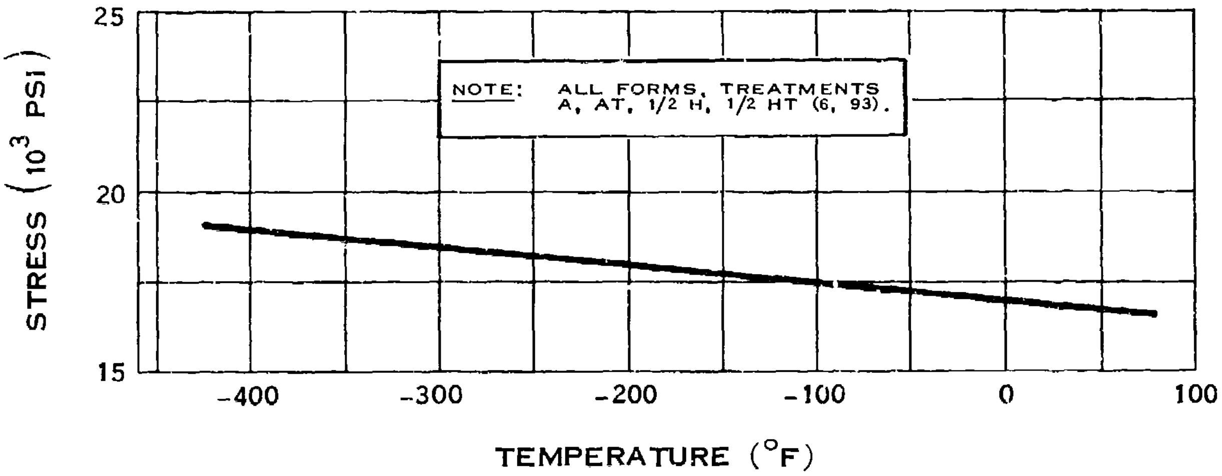
STRESS-STRAIN DIAGRAM FOR BERYLLIUM COPPER

F.2.h-1

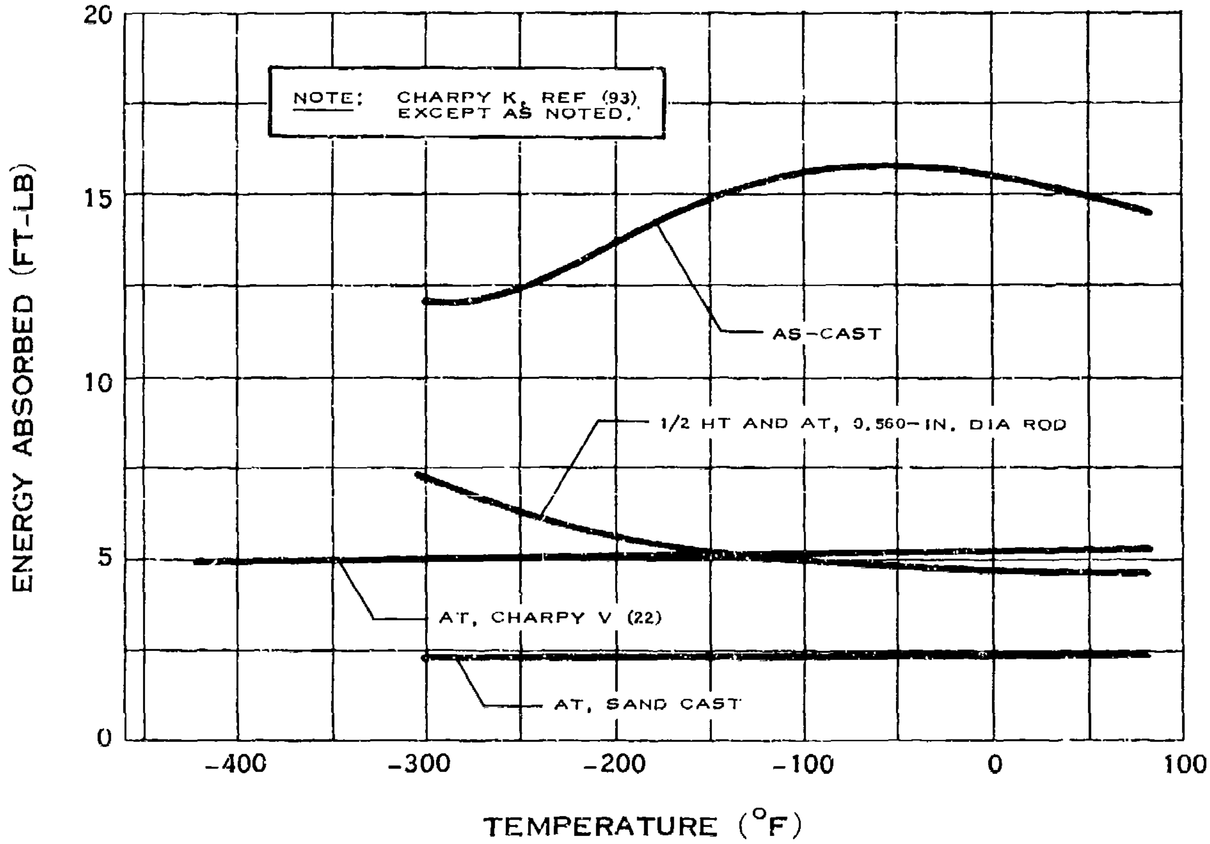


STRESS-STRAIN DIAGRAM FOR BERYLLIUM COPPER

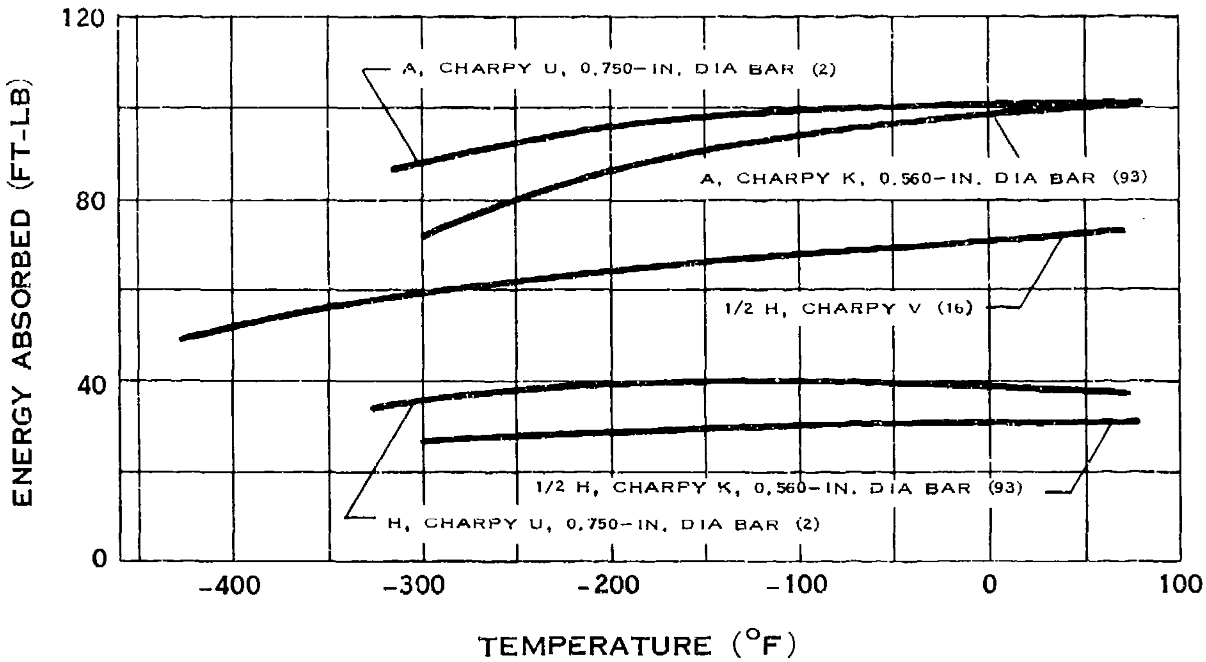
(7-64)



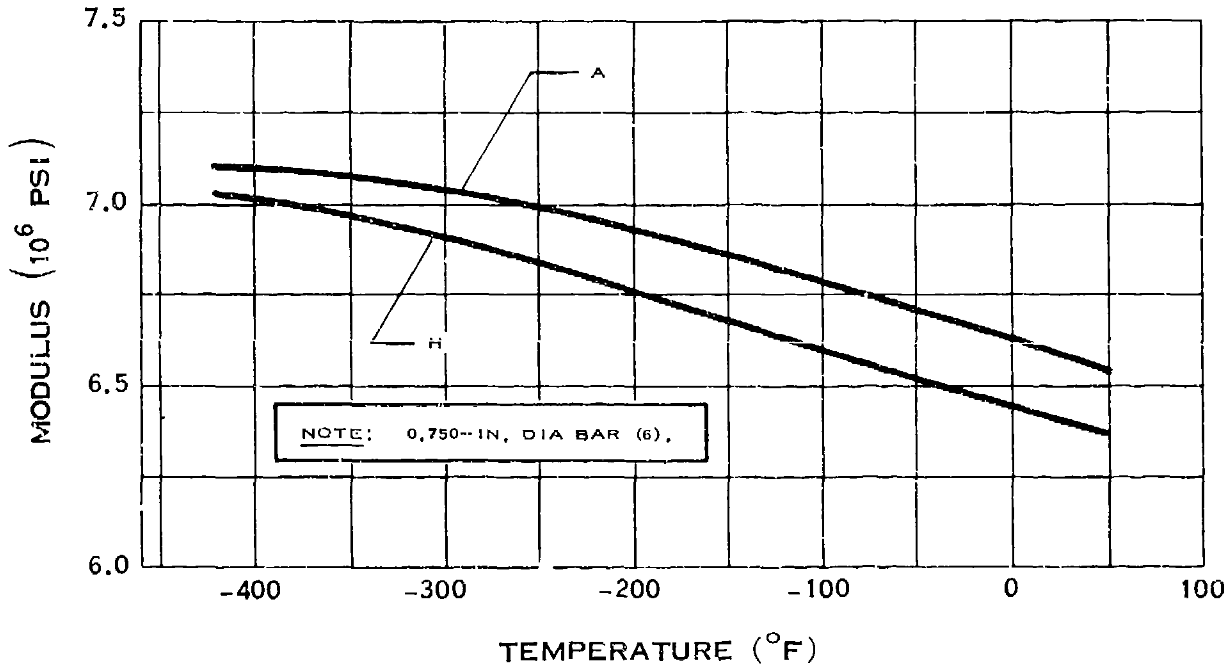
MODULUS OF ELASTICITY OF BERYLLIUM COPPER



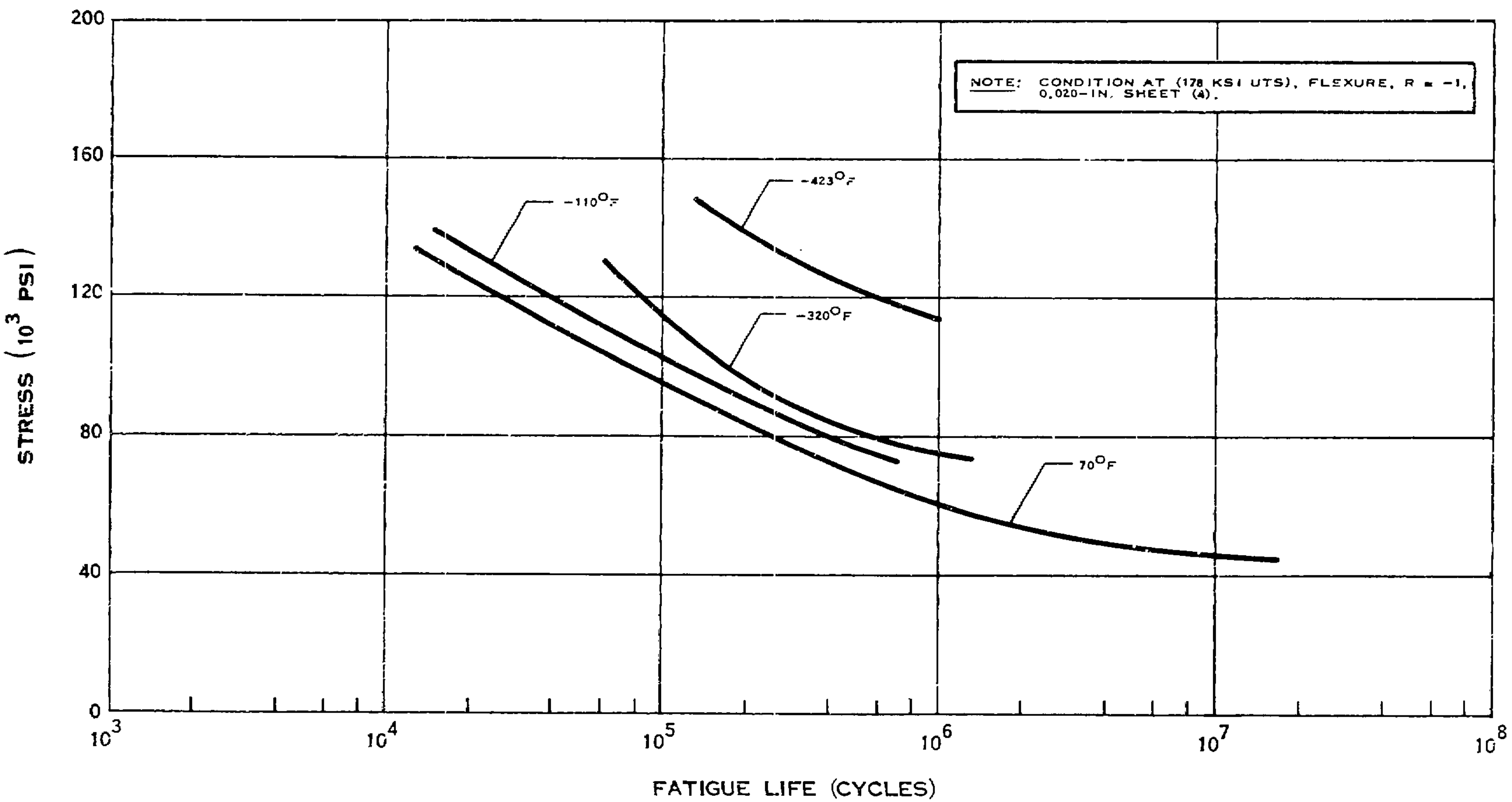
IMPACT STRENGTH OF BERYLLIUM COPPER



IMPACT STRENGTH OF BERYLLIUM COPPER

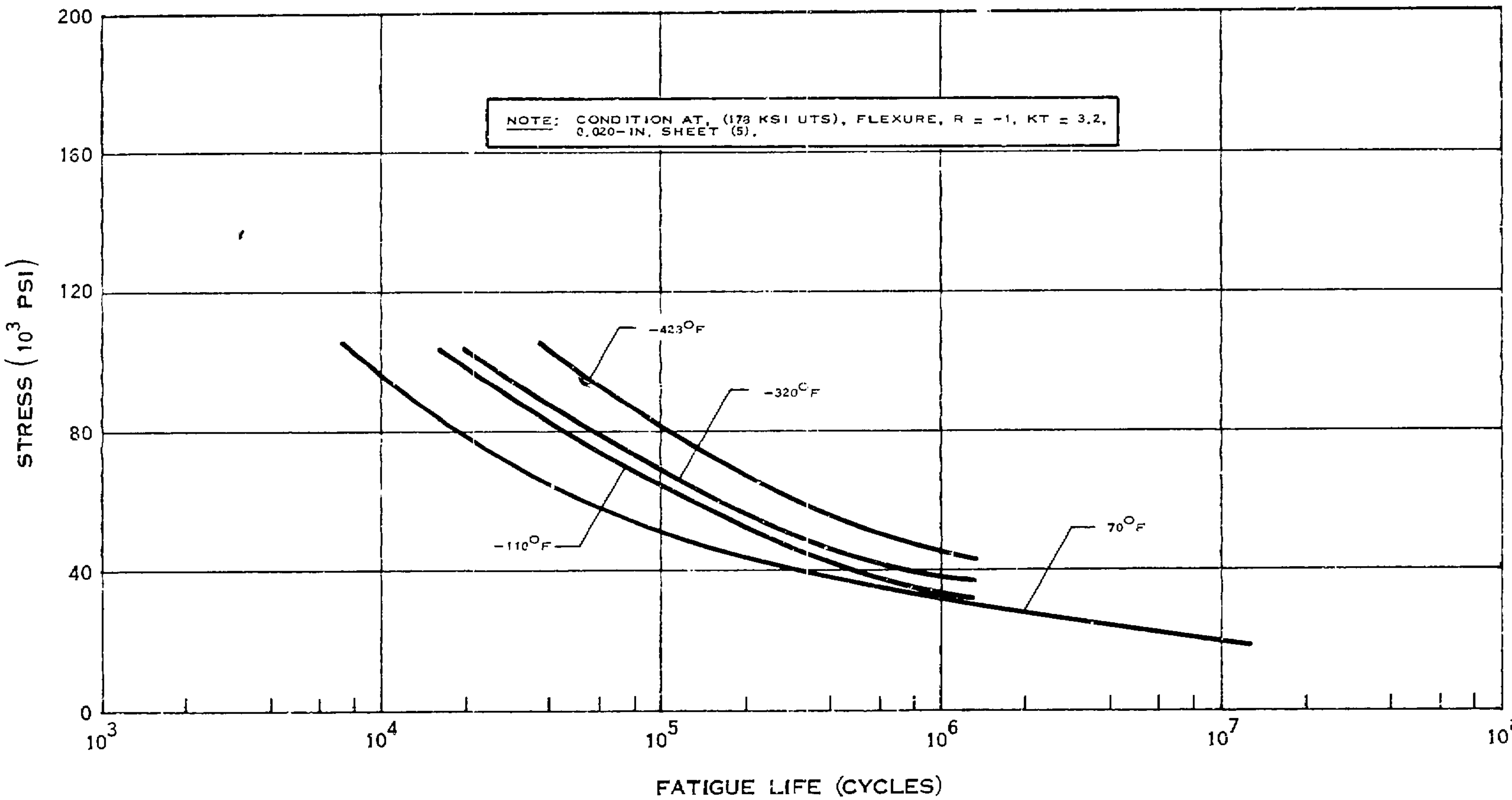


MODULUS OF RIGIDITY OF BERYLLIUM COPPER



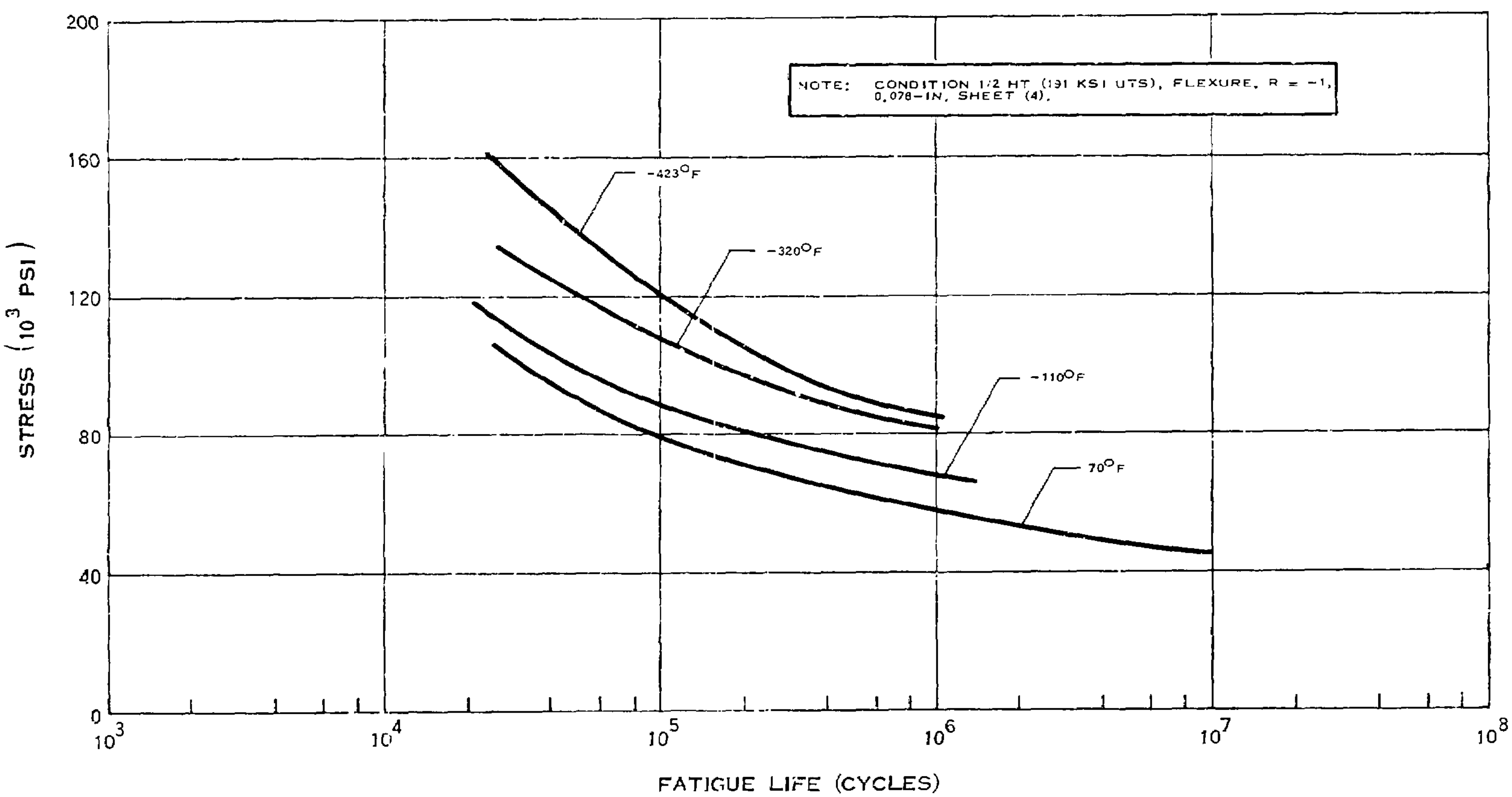
FATIGUE STRENGTH OF BERYLLIUM COPPER

(7-64)



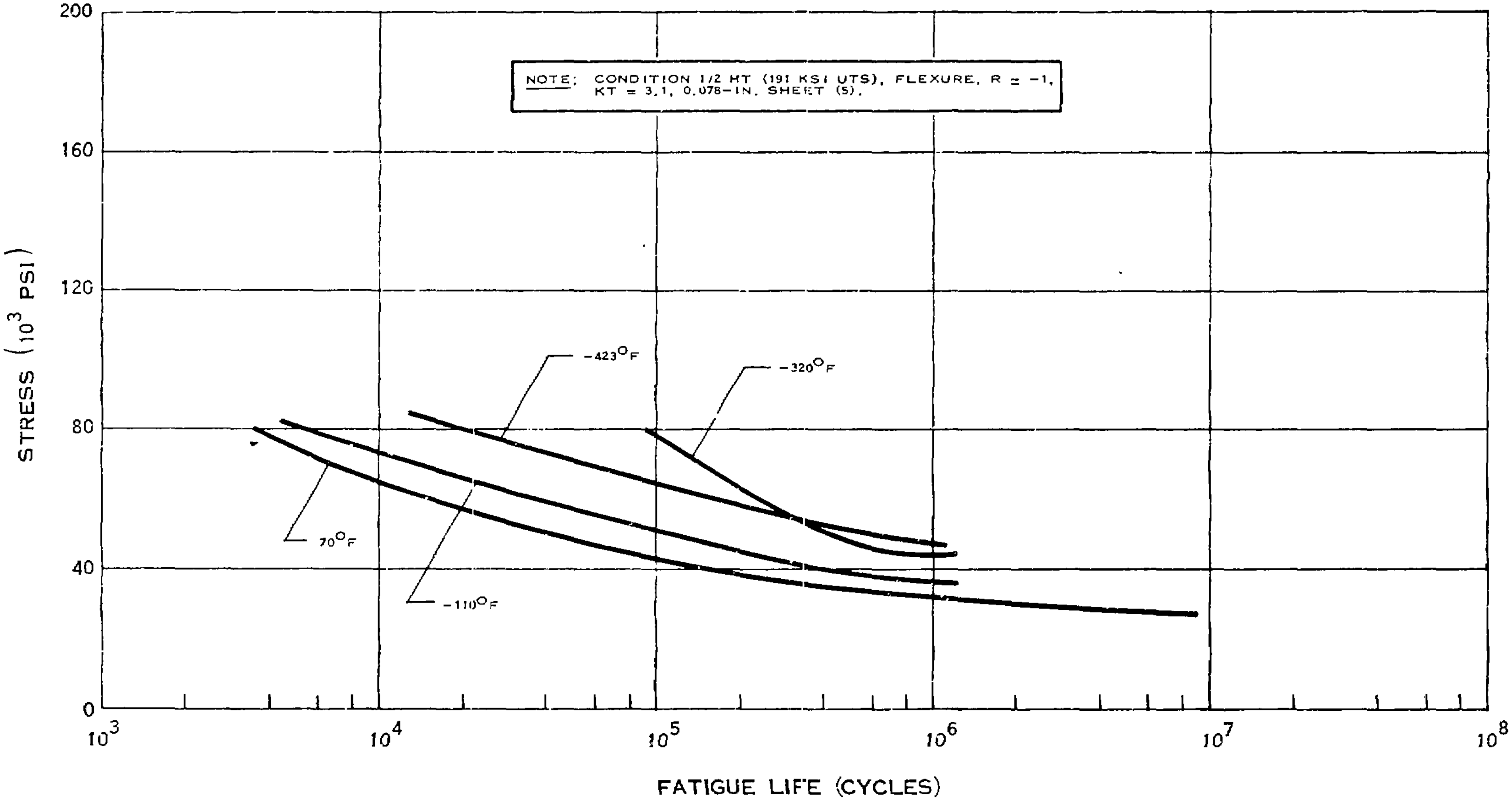
NOTCH FATIGUE STRENGTH OF BERYLLIUM COPPER

(7–64)



FATIGUE STRENGTH OF BERYLLIUM COPPER

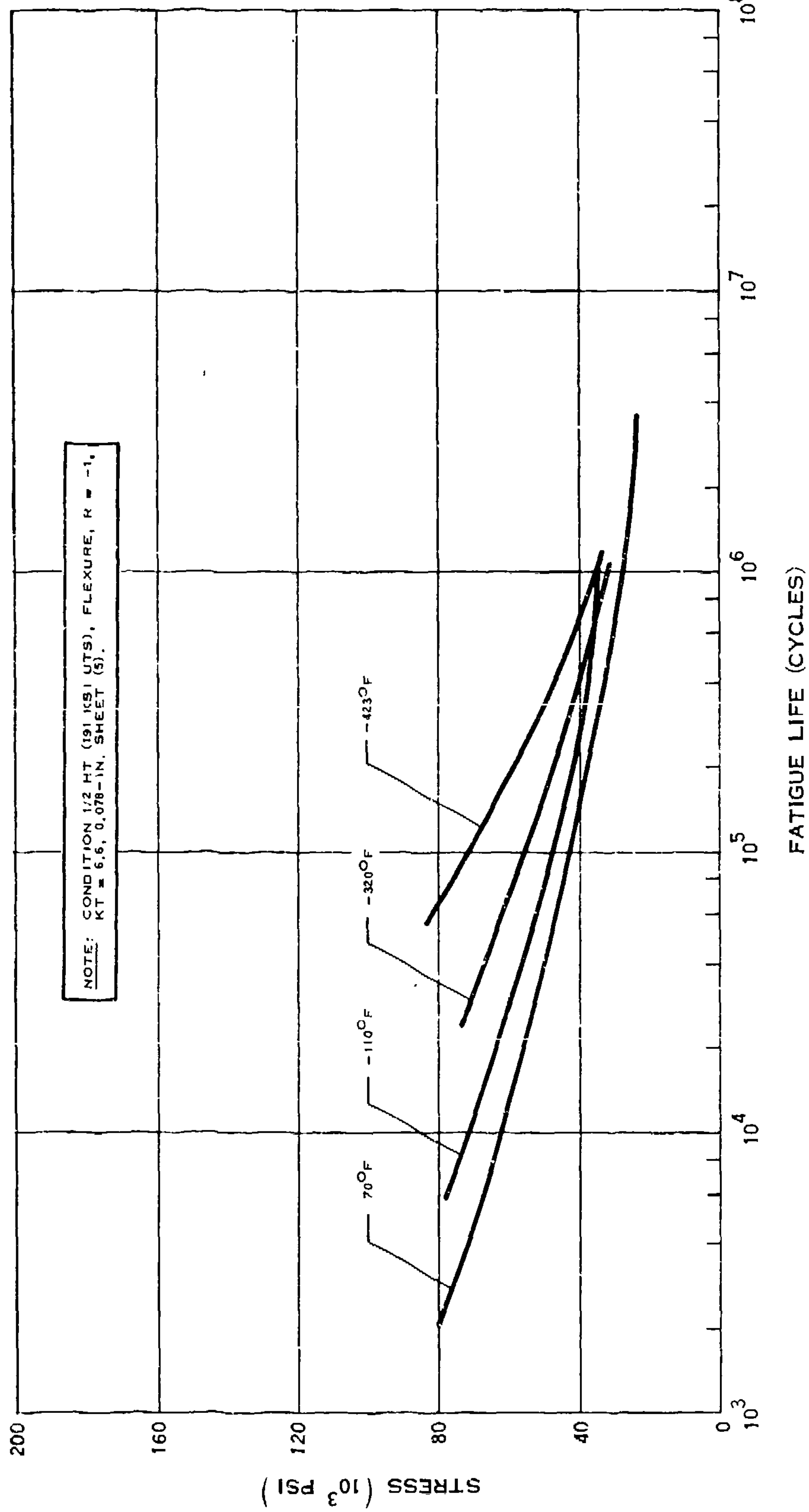
(7-64)



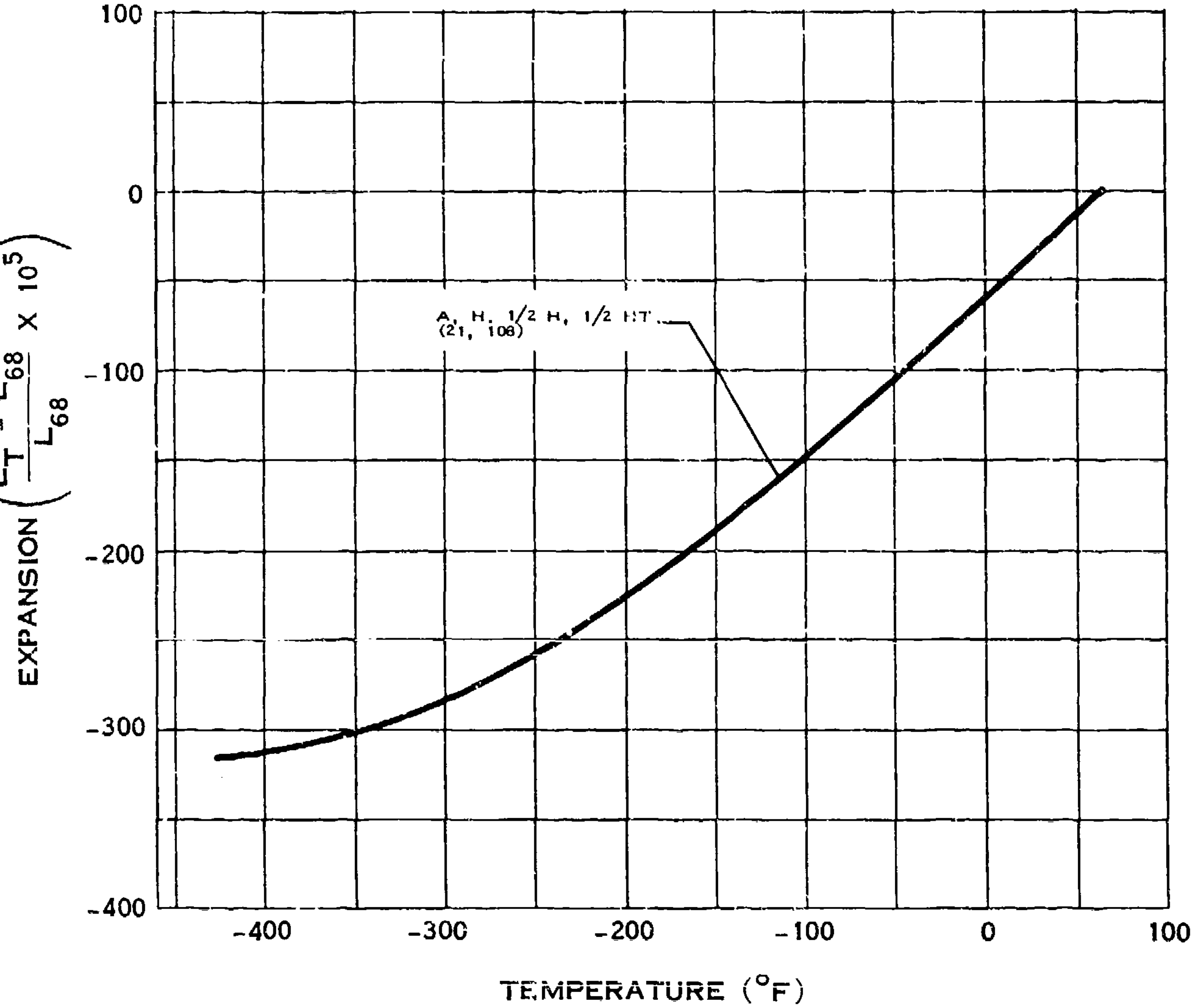
NOTCH FATIGUE STRENGTH OF BERYLLIUM COPPER

(7-64)

F.2.o-4

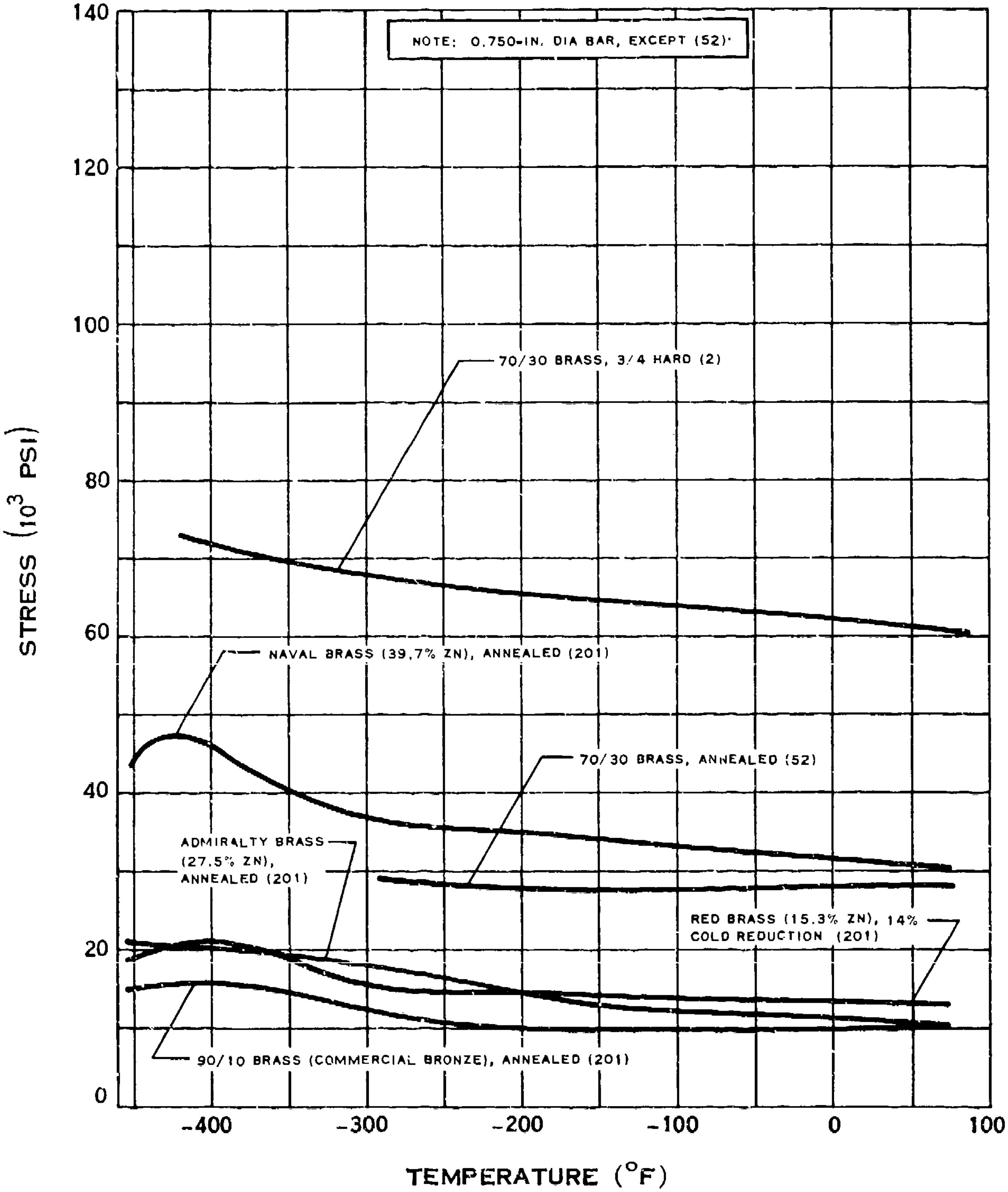


NOTCH FATIGUE STRENGTH OF BERYLLIUM COPPER



THERMAL EXPANSION OF BERYLLIUM COPPER

(7-64)



YIELD STRENGTH OF BRASS

(6-68)

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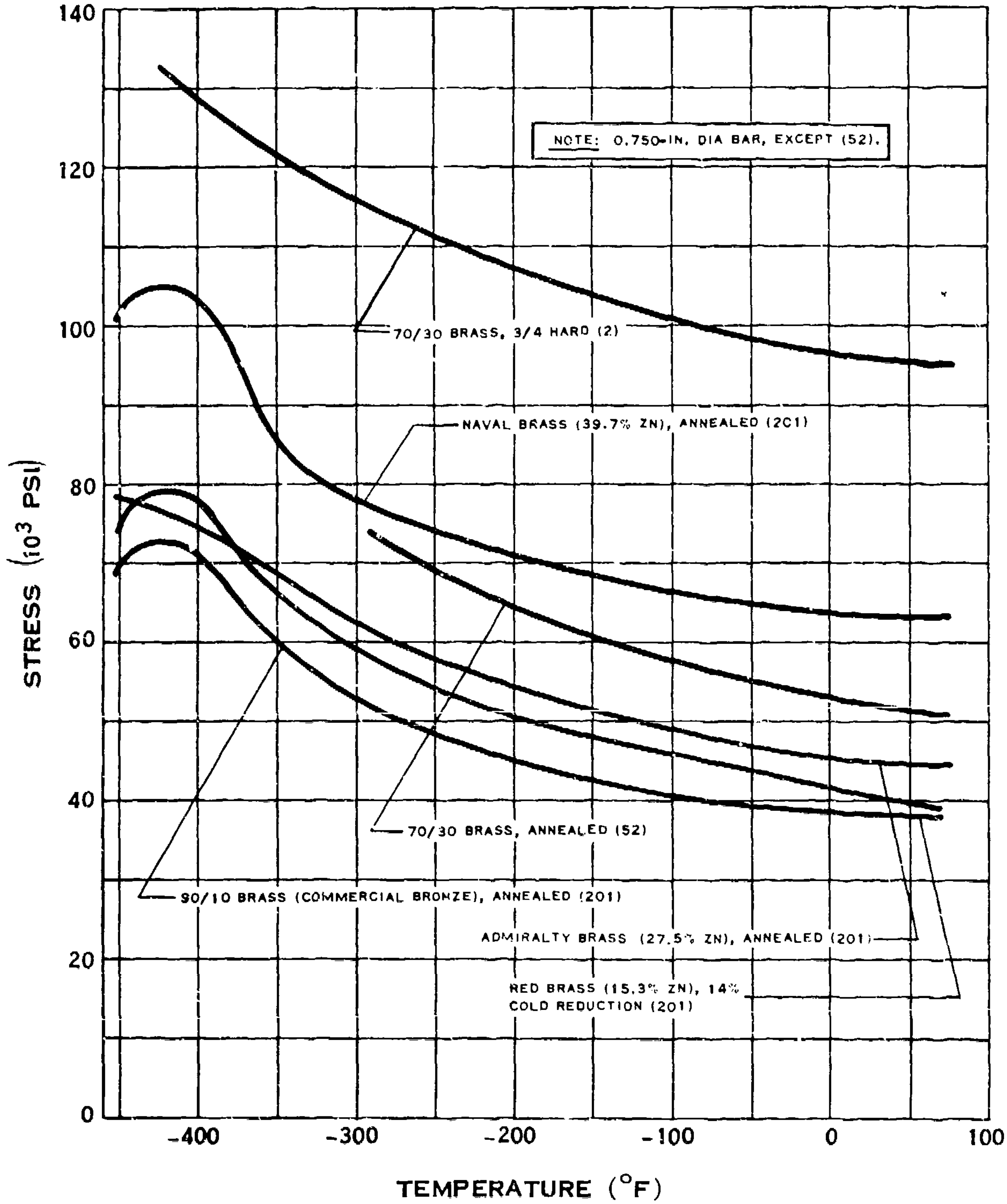
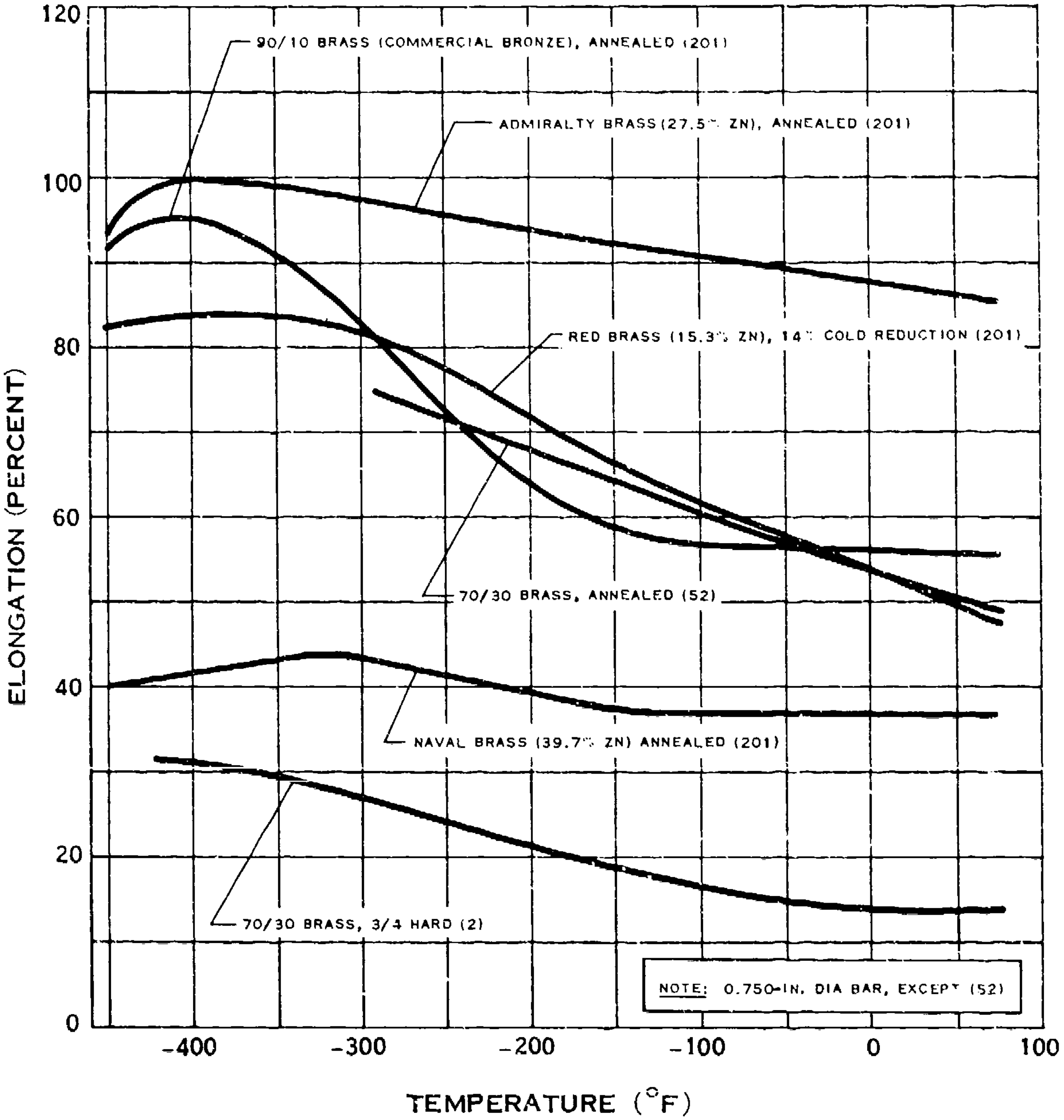


TENSILE STRENGTH OF BRASS

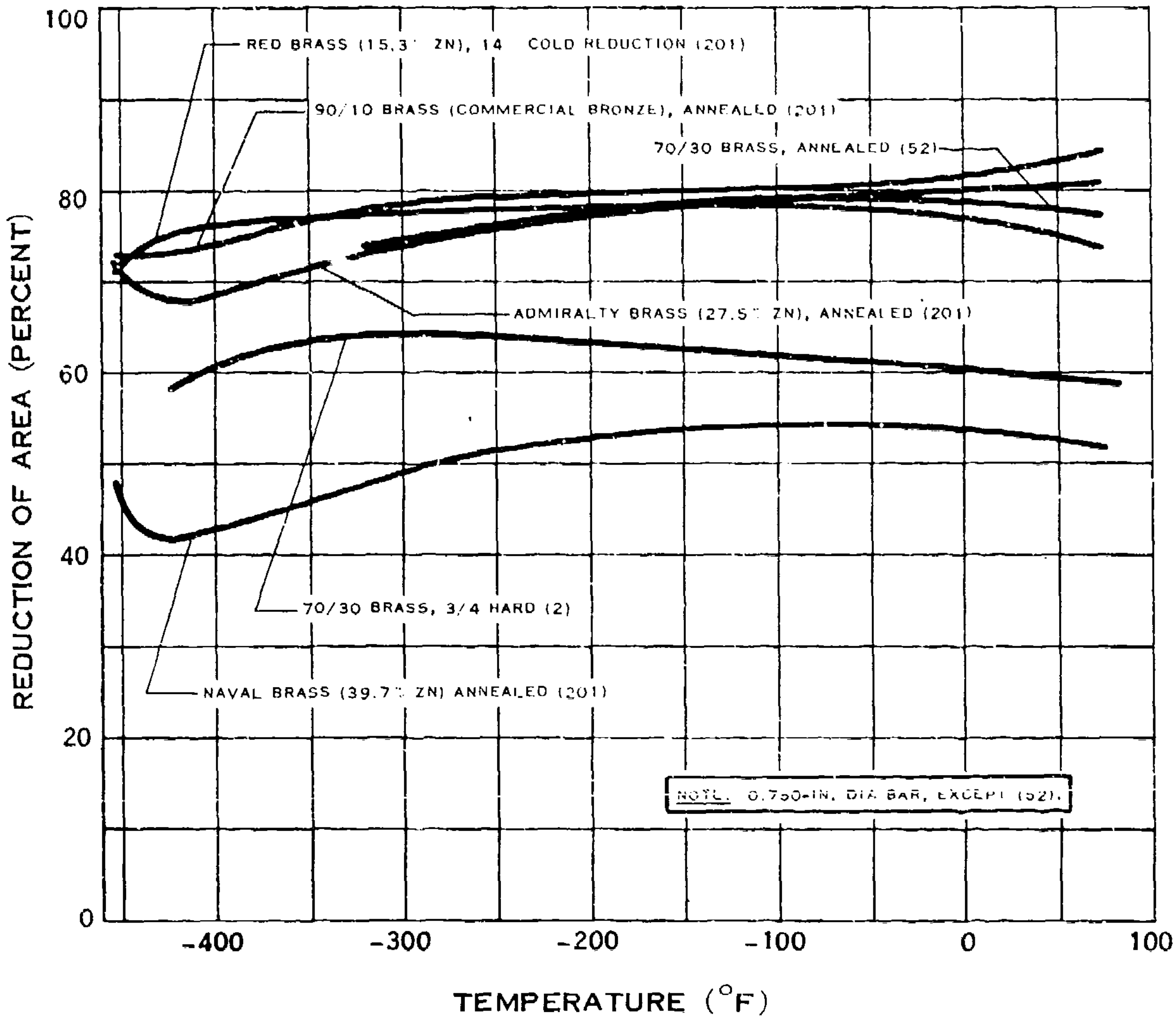
(6-68)



ELONGATION OF BRASS

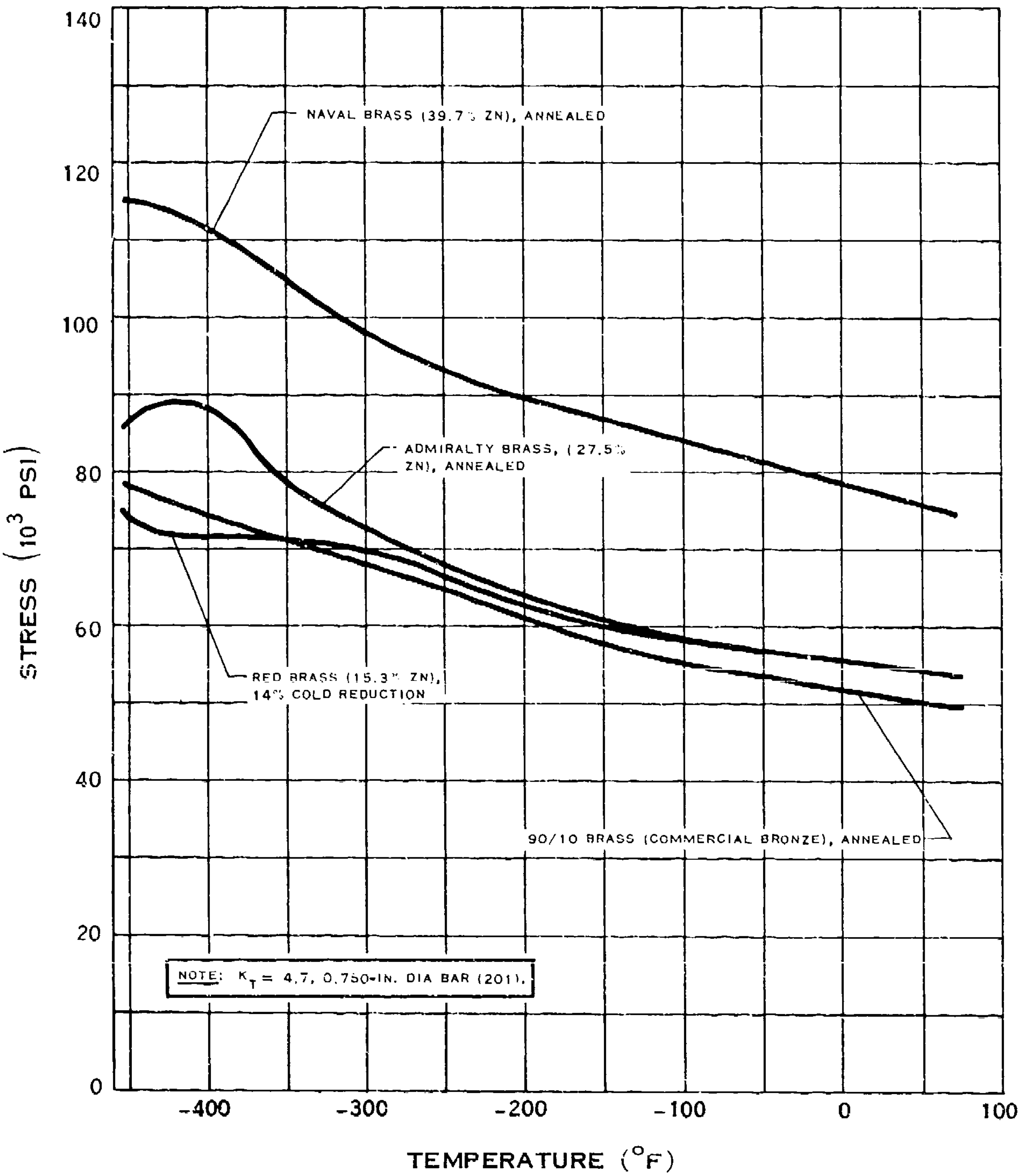
(6-68)

F.3.d



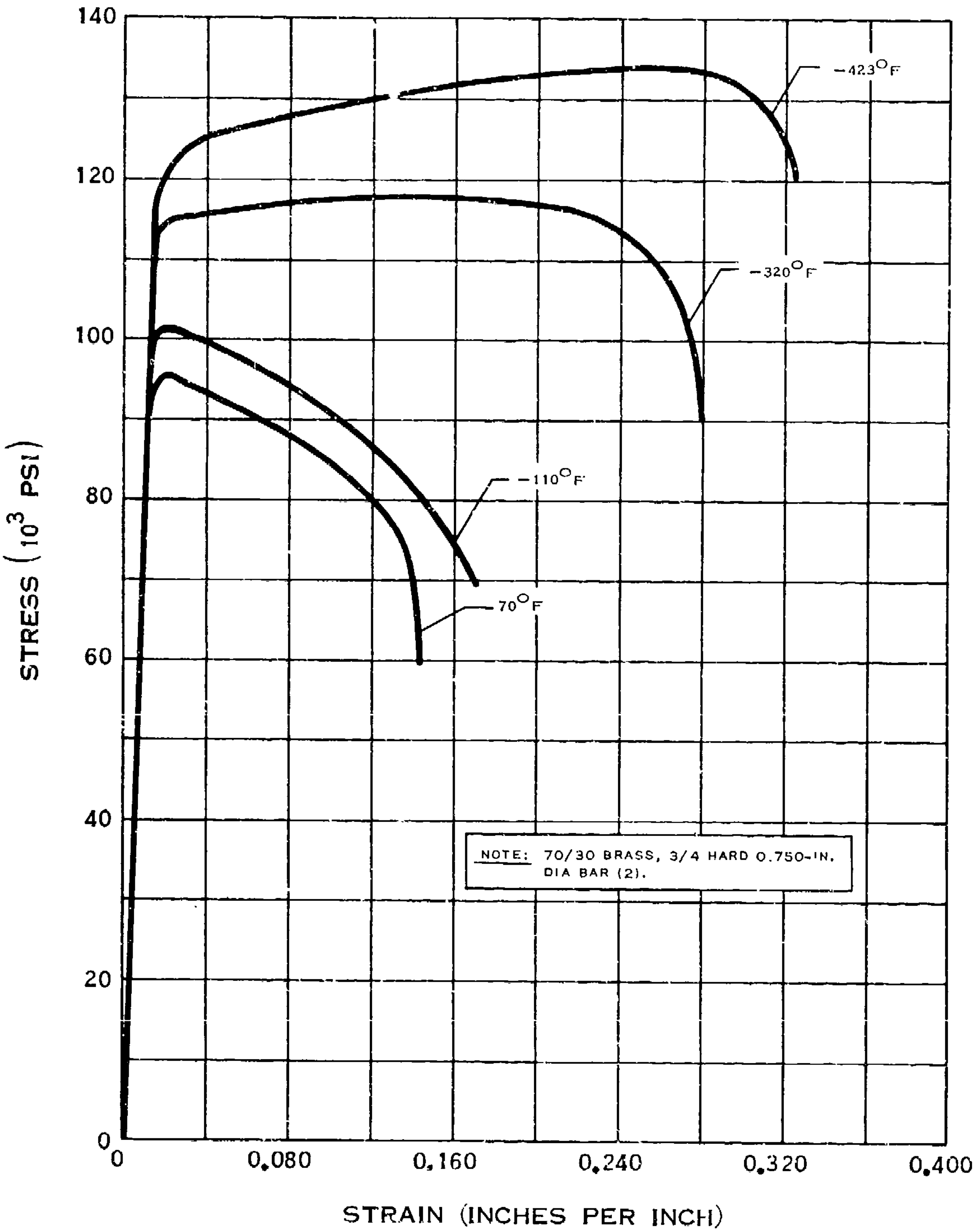
REDUCTION OF AREA OF BRASS

(6-68)



NOTCH TENSILE STRENGTH OF BRASS

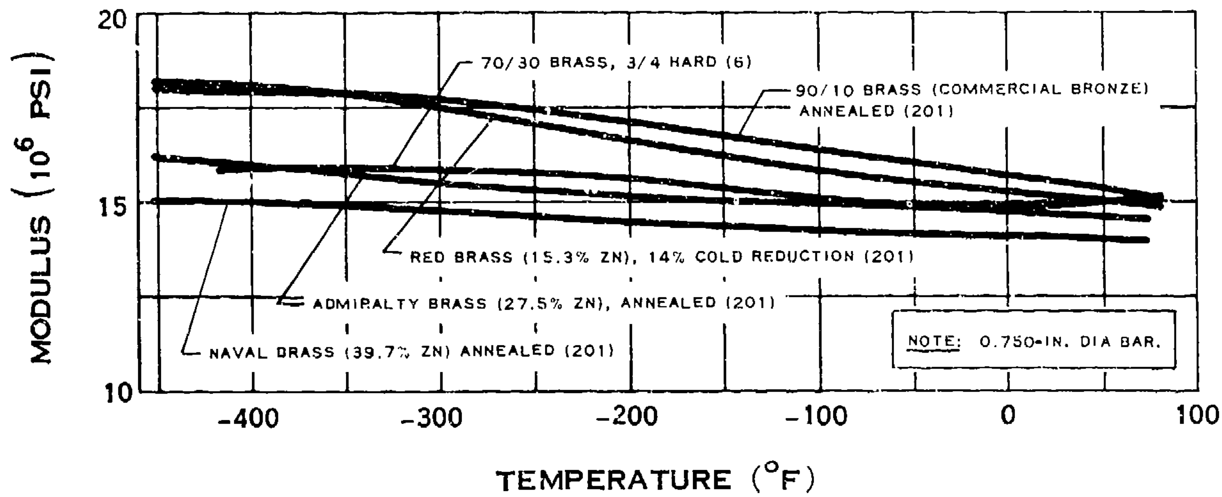
(6-68)



STRESS-STRAIN DIAGRAM FOR BRASS

(6-68)

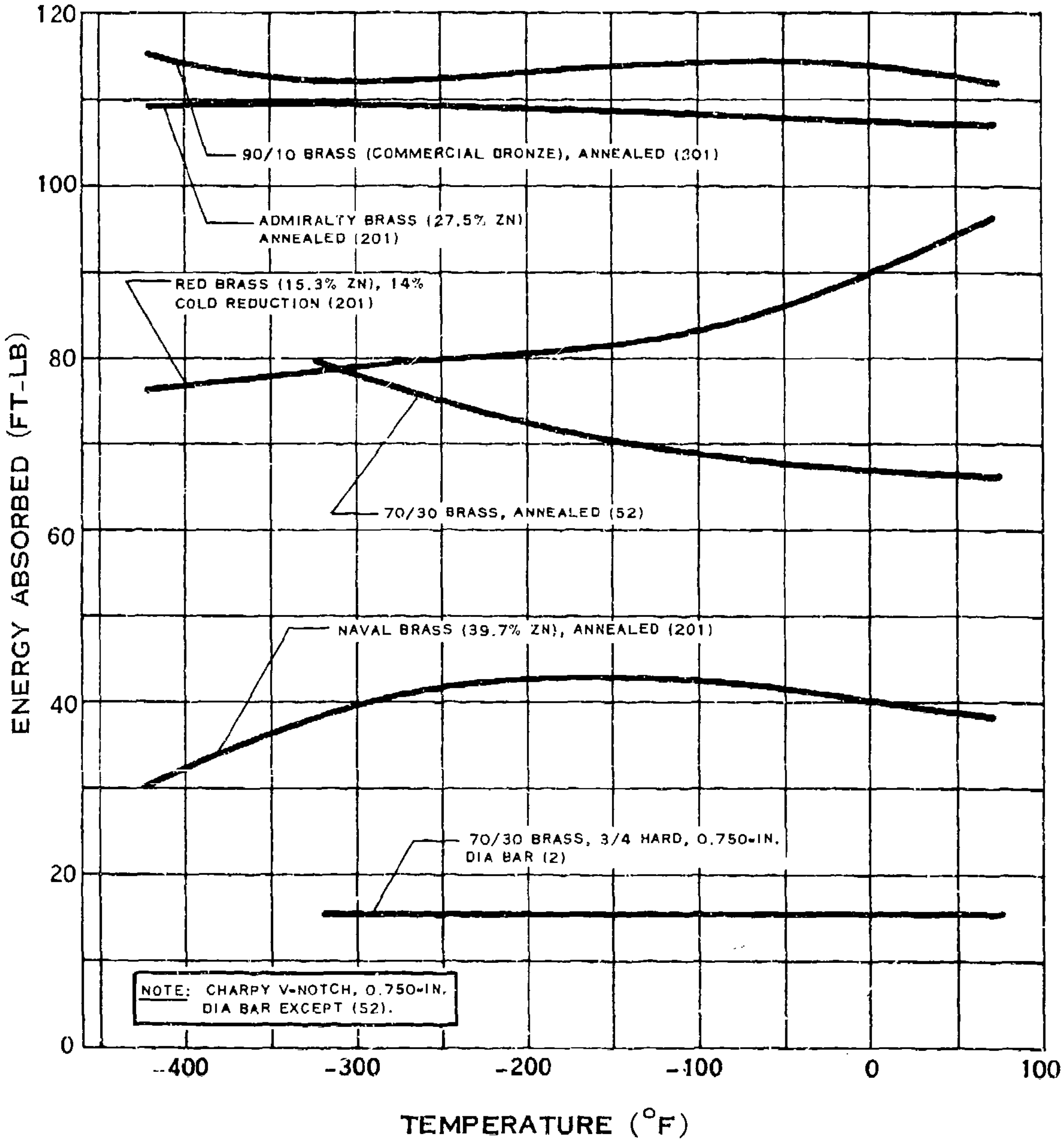
F.3.i



MODULUS OF ELASTICITY OF BRASS

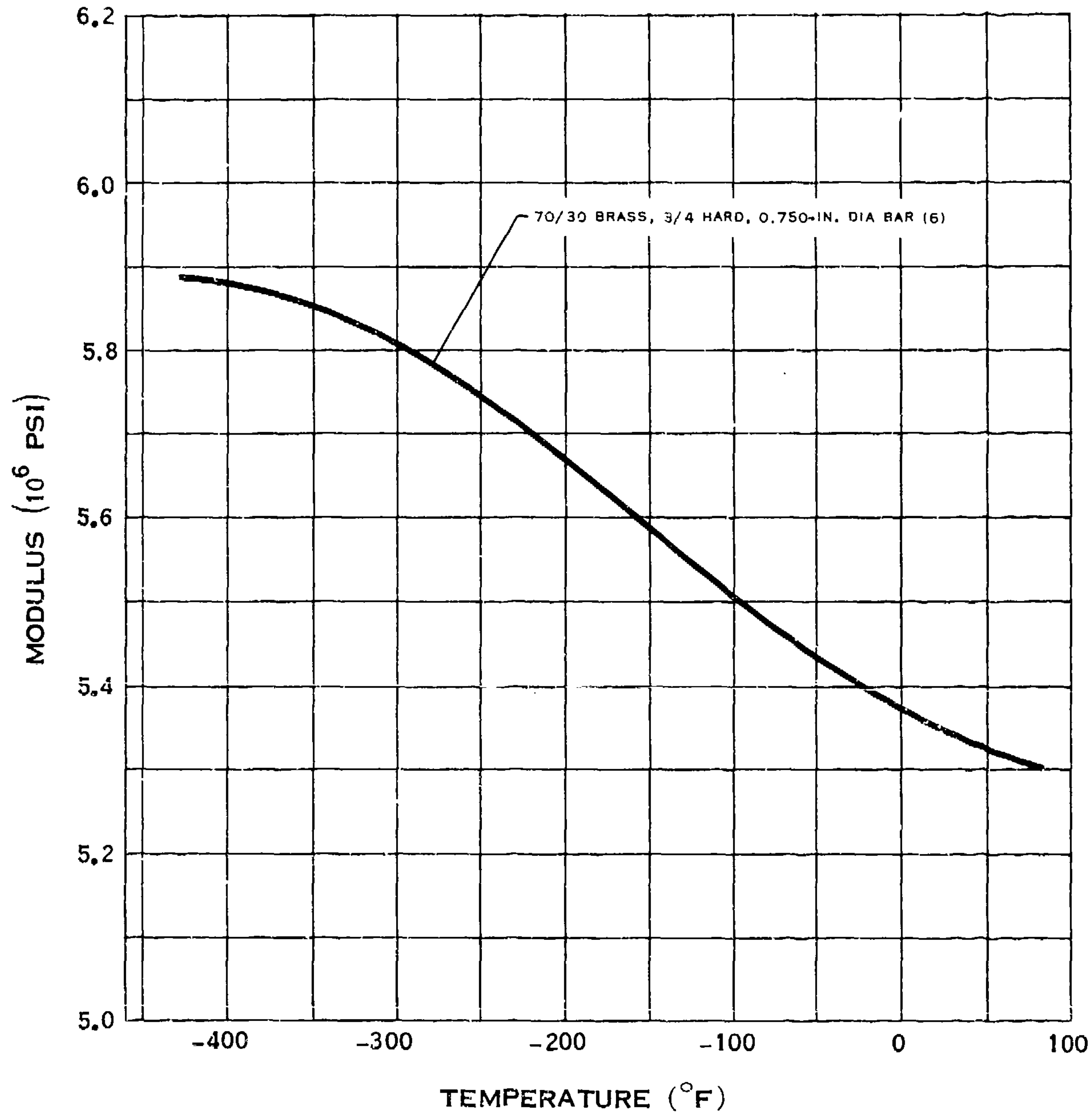
(6-68)

F.3.j



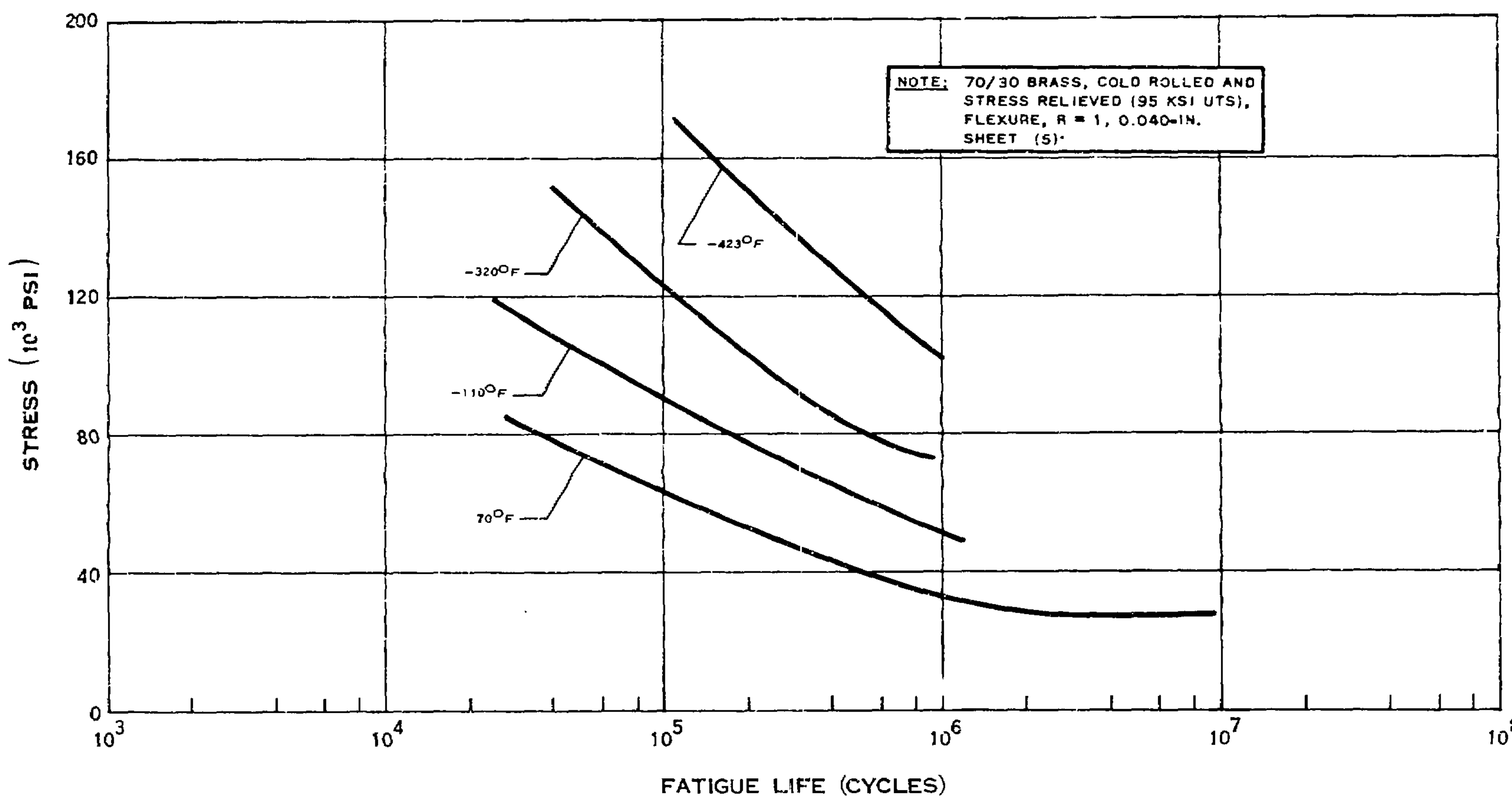
IMPACT STRENGTH OF BRASS

(6-68)



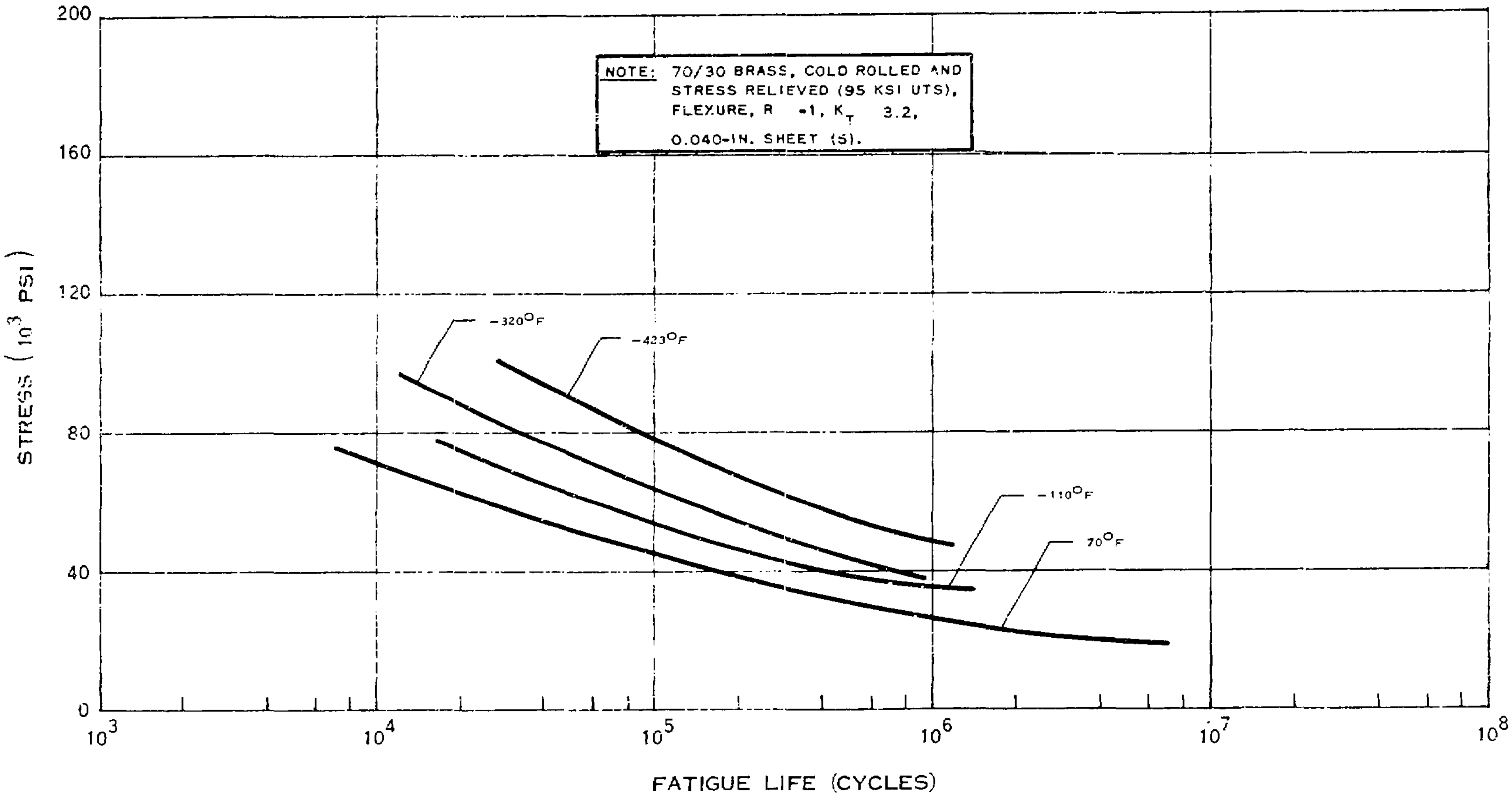
MODULUS OF RIGIDITY OF BRASS

(6-68)



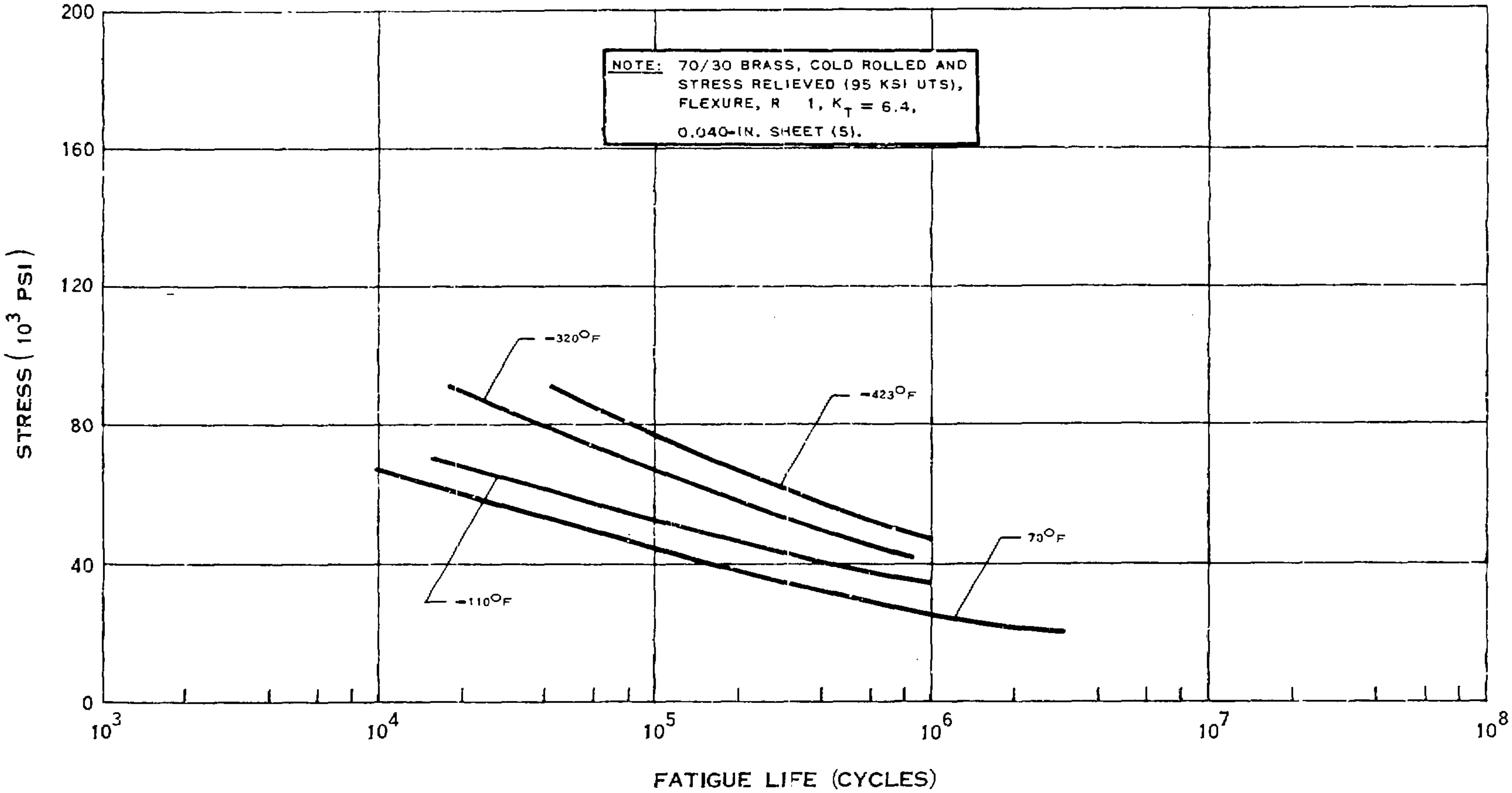
FATIGUE STRENGTH OF BRASS

(6-68)



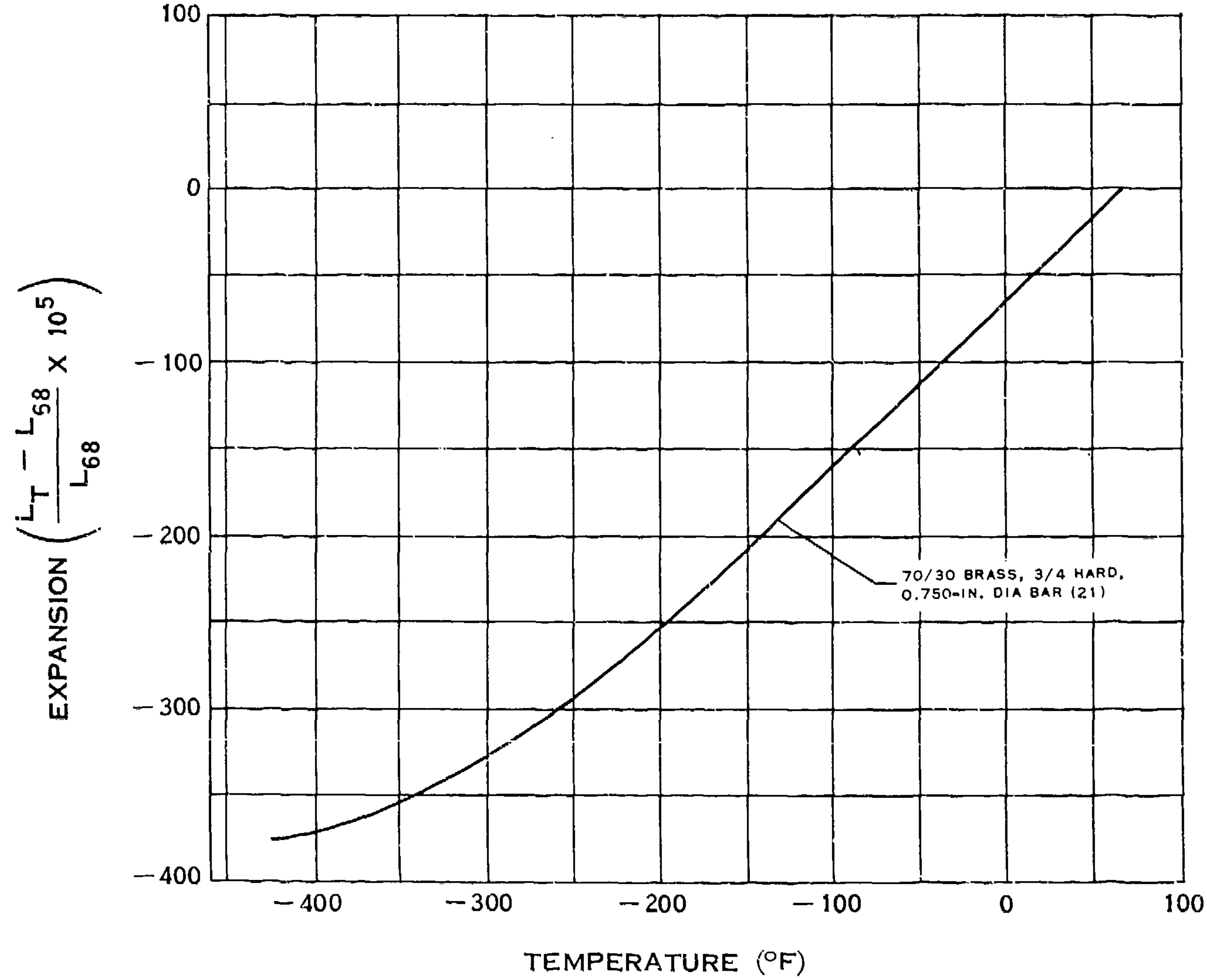
NOTCH FATIGUE STRENGTH OF BRASS

(6-68)



NOTCH FATIGUE STRENGTH OF BRASS

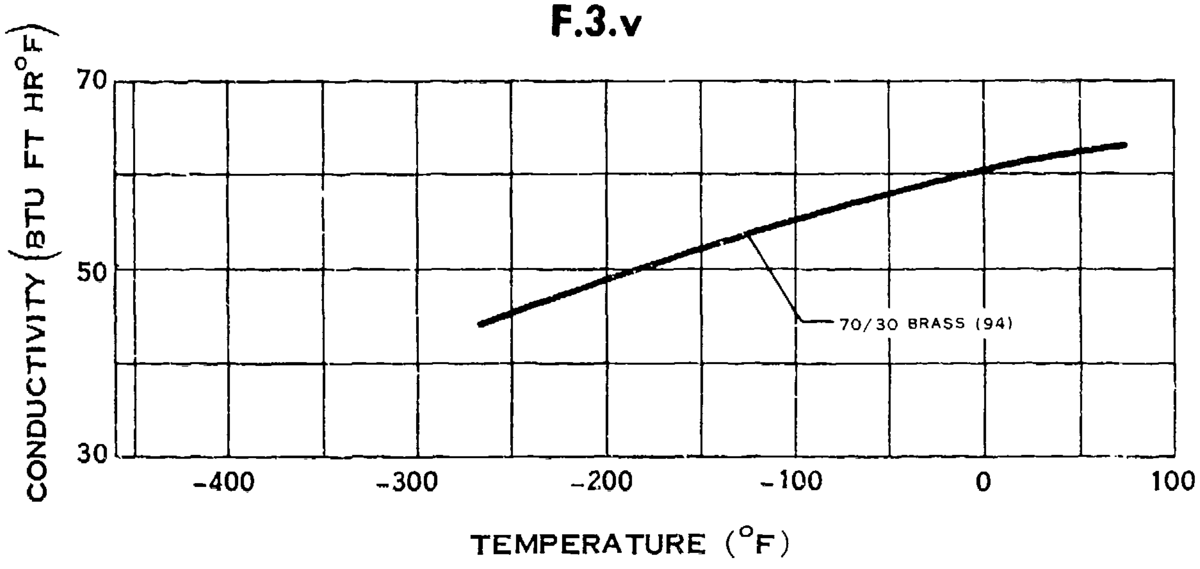
(6-68)



THERMAL EXPANSION OF BRASS

(G-68)

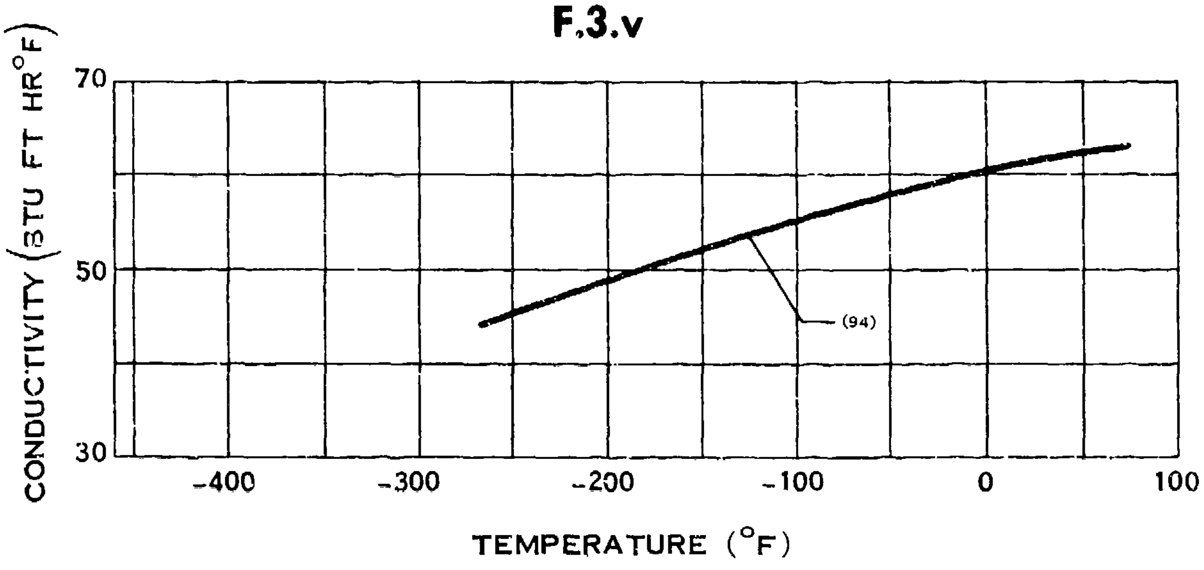
F.3.v



THERMAL CONDUCTIVITY OF BRASS

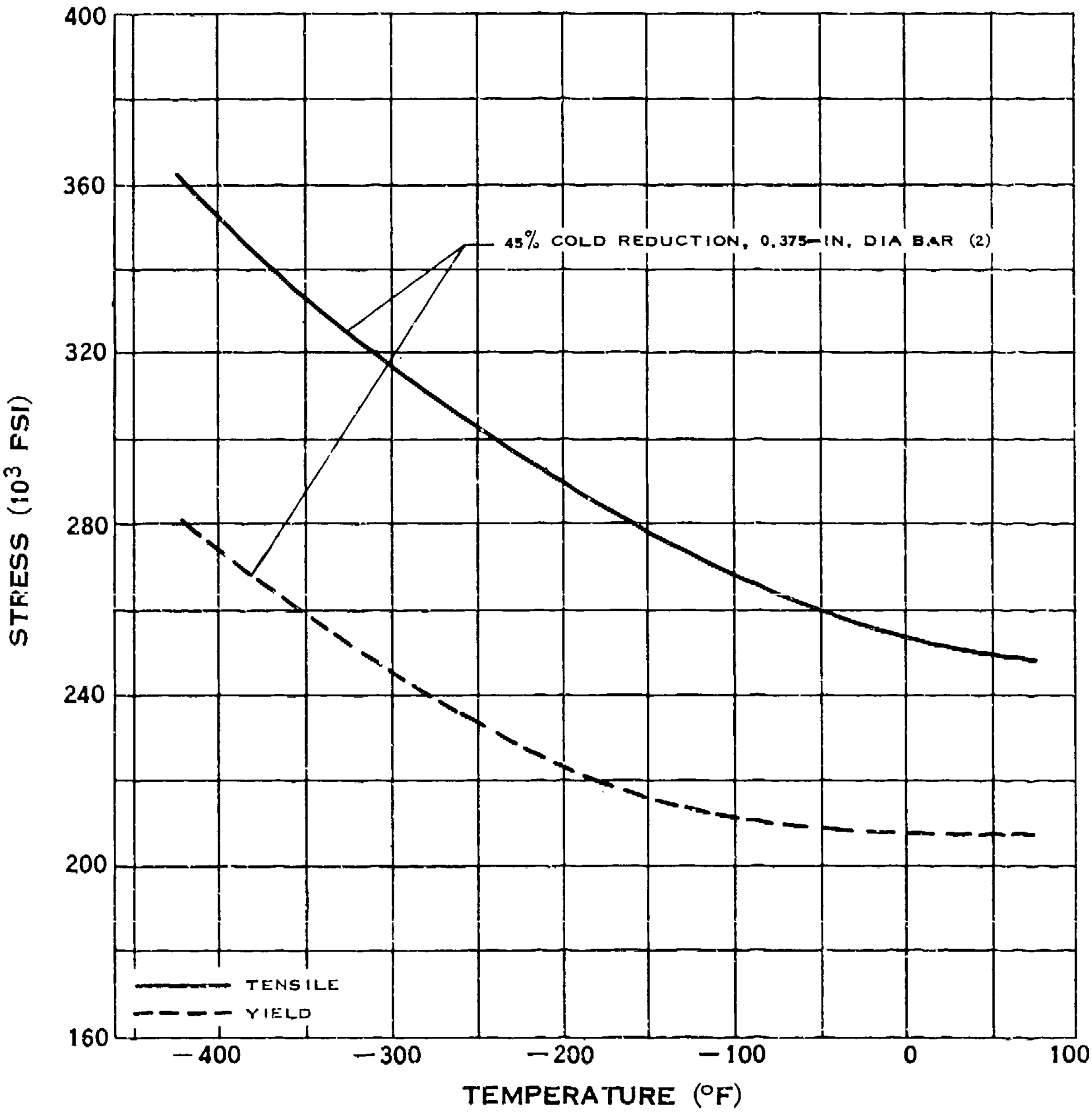
(5-66)

F.3.v



THERMAL CONDUCTIVITY OF 70/30 BRASS

F.4.ab



STRENGTH OF ELGILOY*

* T.M.
ELGIN NATIONAL WATCH CO.

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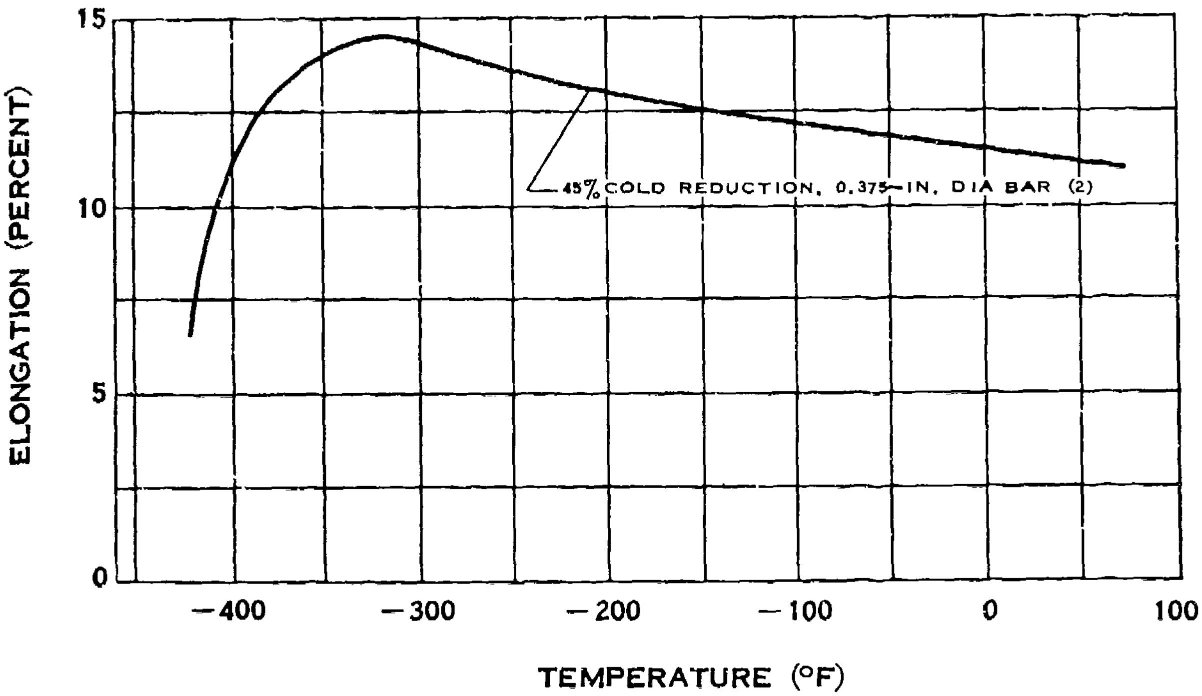
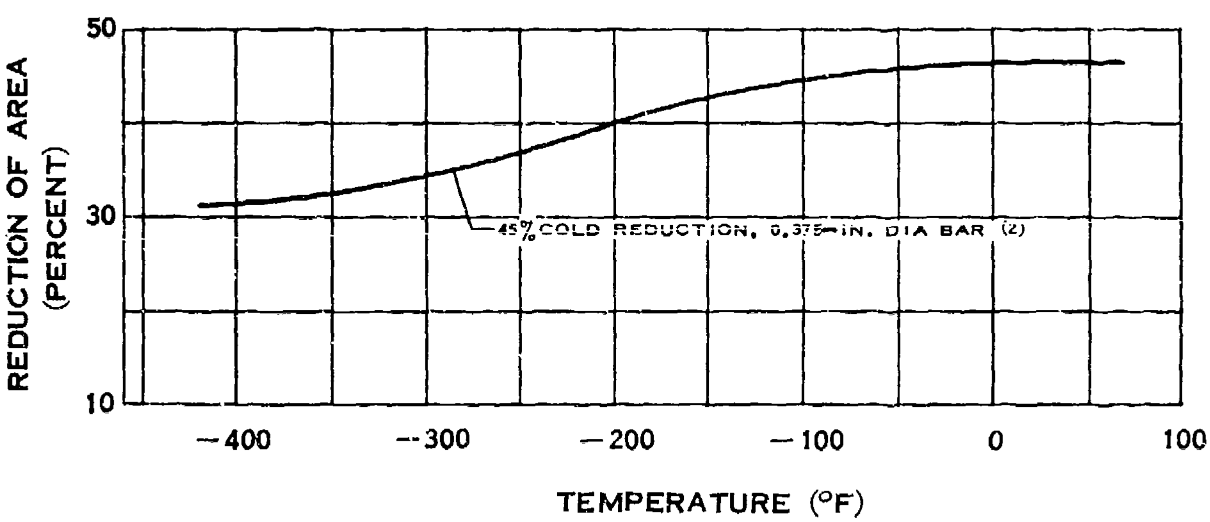
F.4.cd



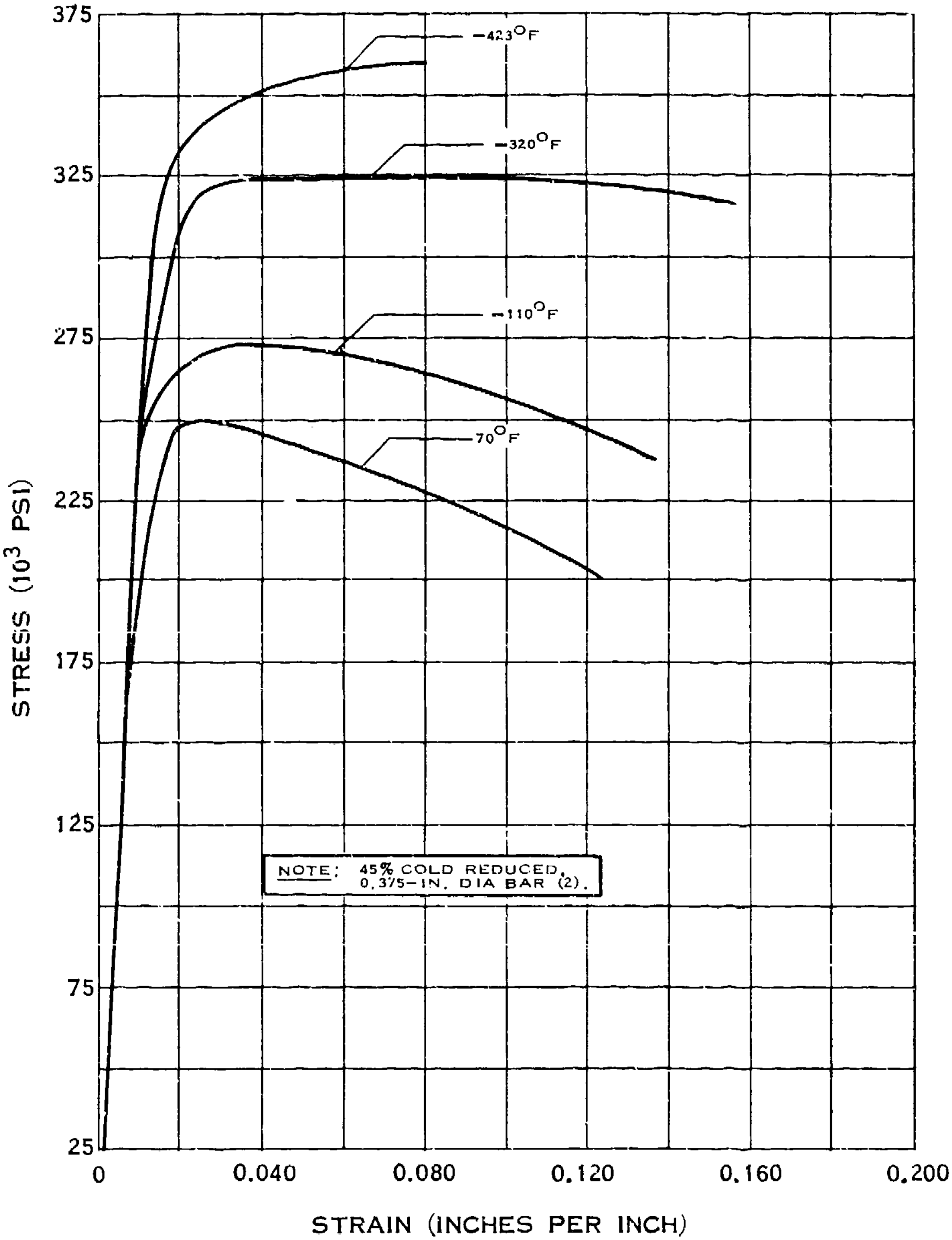
ELONGATION OF ELGILOY*



REDUCTION OF AREA OF ELGILOY*

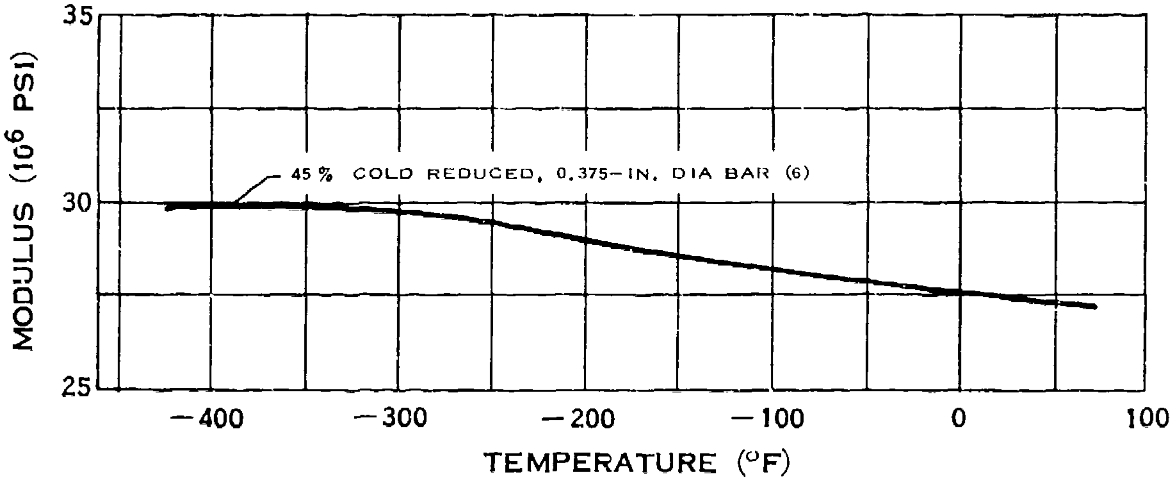
* T.M. ELGIN NATIONAL WATCH CO.

F.4.h

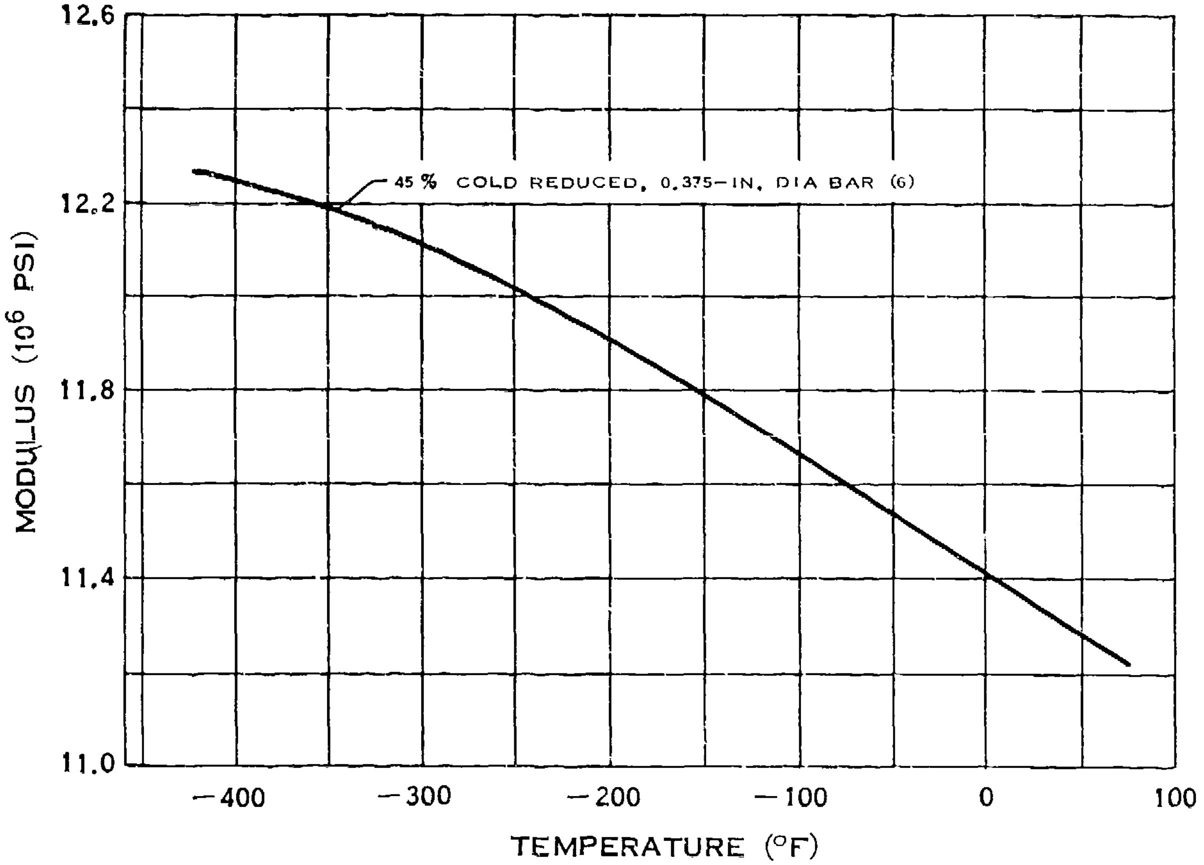


STRESS-STRAIN DIAGRAM FOR ELGILOY*

* T.M.
ELGIN NATIONAL WATCH CO.

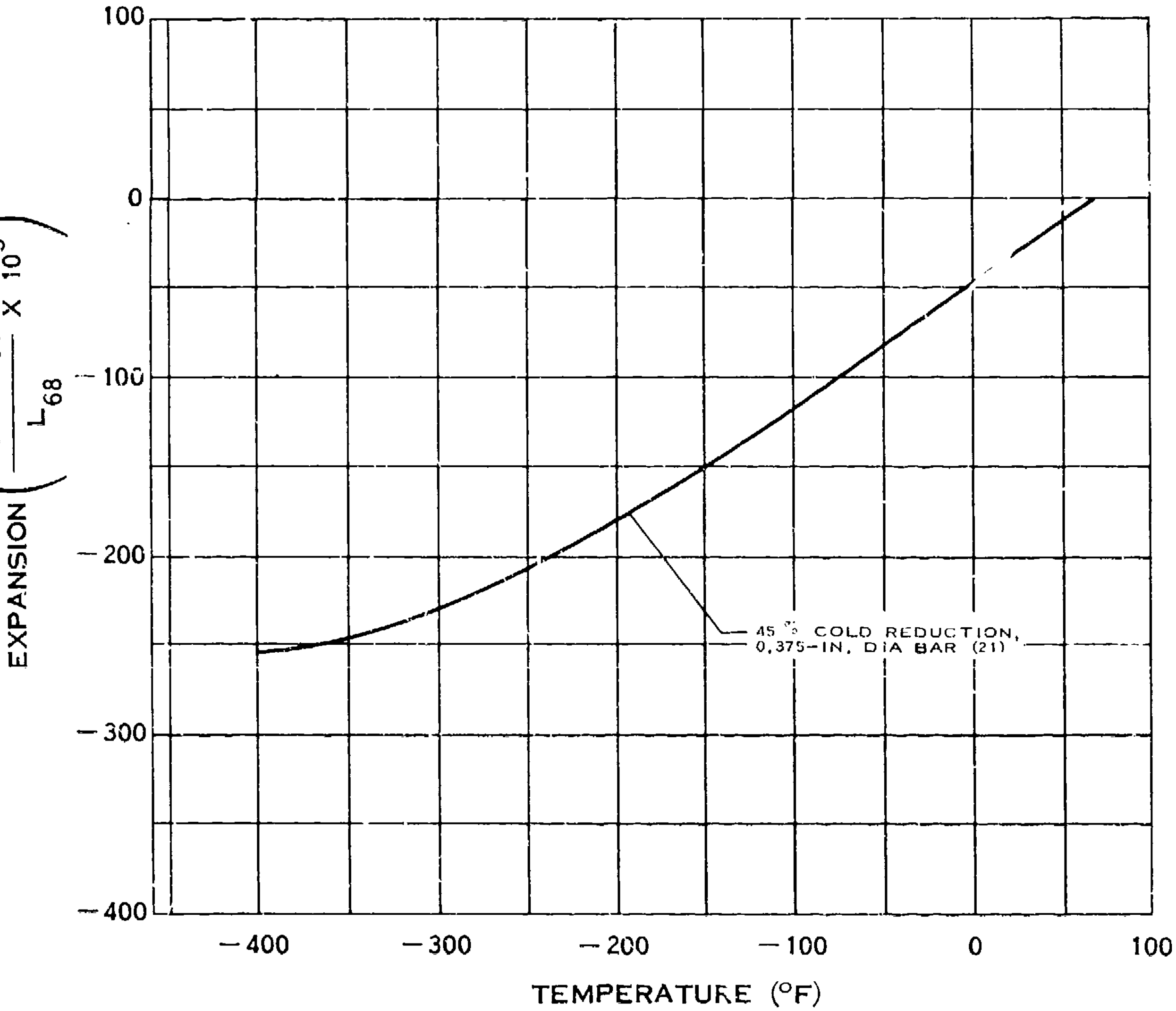


MODULUS OF ELASTICITY OF ELGILOY*



MODULUS OF RIGIDITY OF ELGILOY*

*T.M. ELGIN NATIONAL WATCH CO.

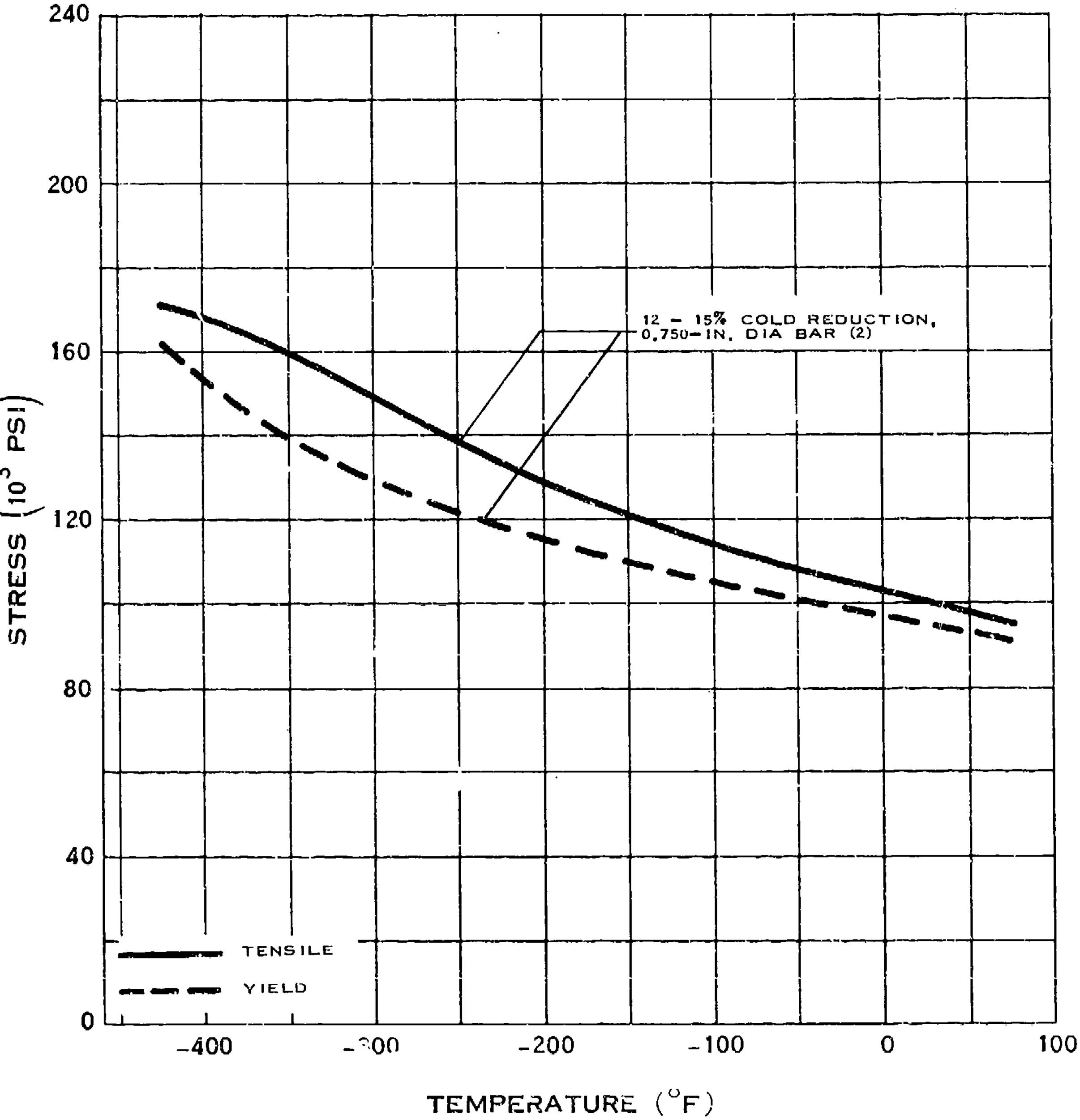


THERMAL EXPANSION OF ELGILOY*

* T.M. ELGIN NATIONAL WATCH CO.

(7-64)

F.5.ab



STRENGTH OF INVAR

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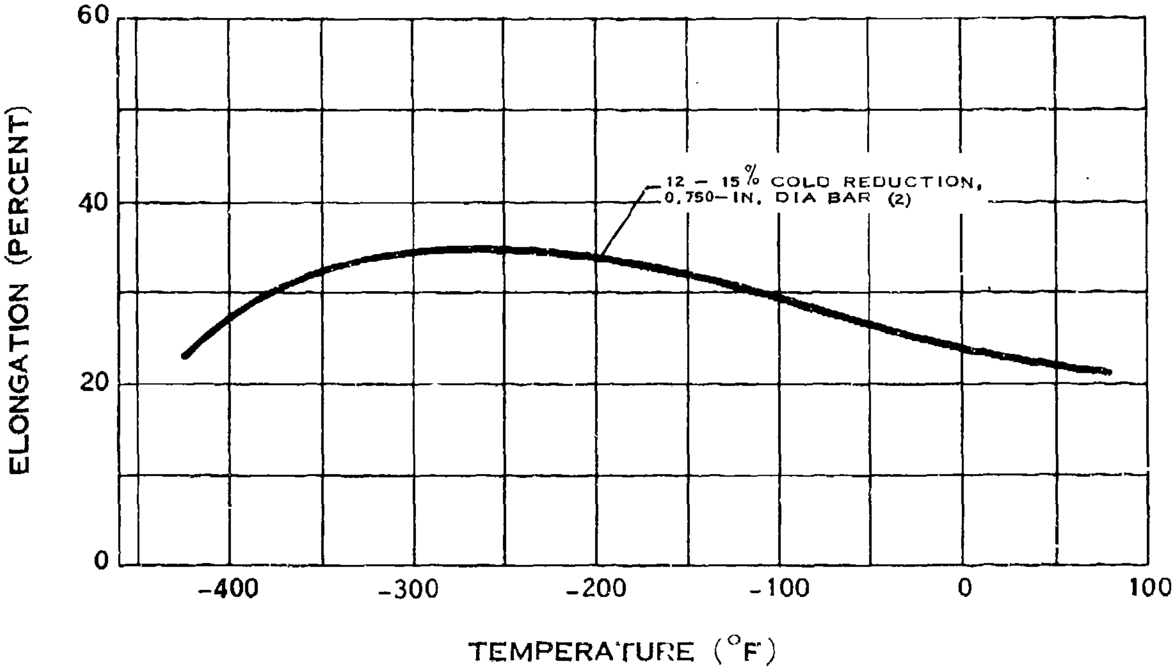
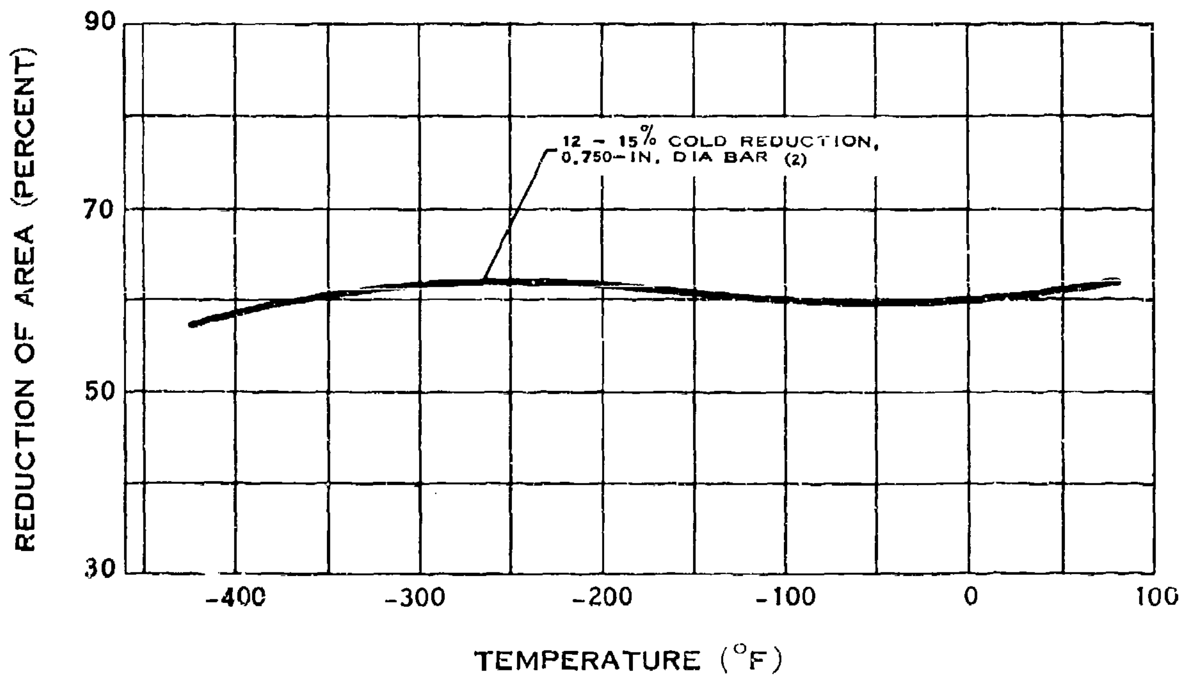
F.5.cd

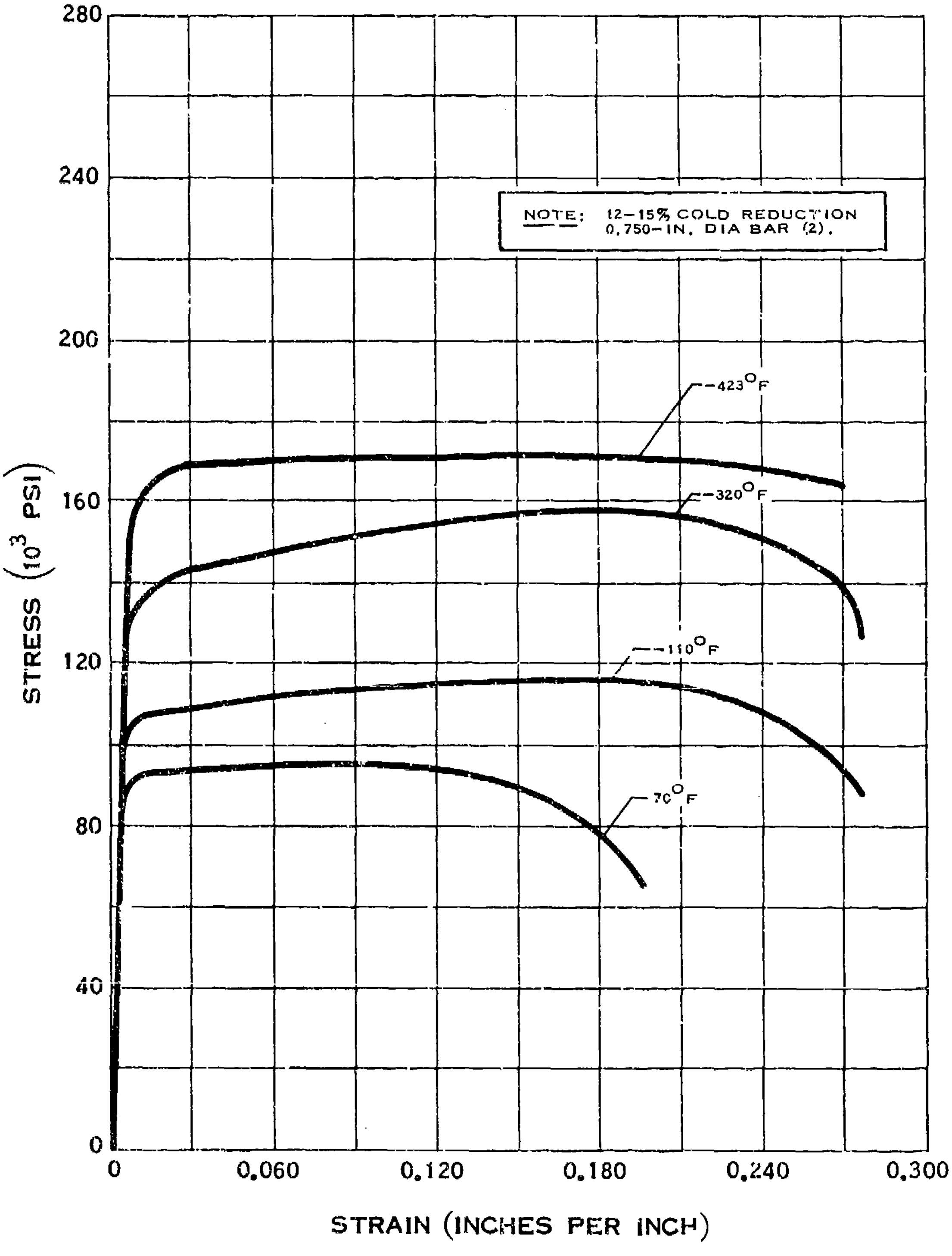


ELONGATION OF INVAR

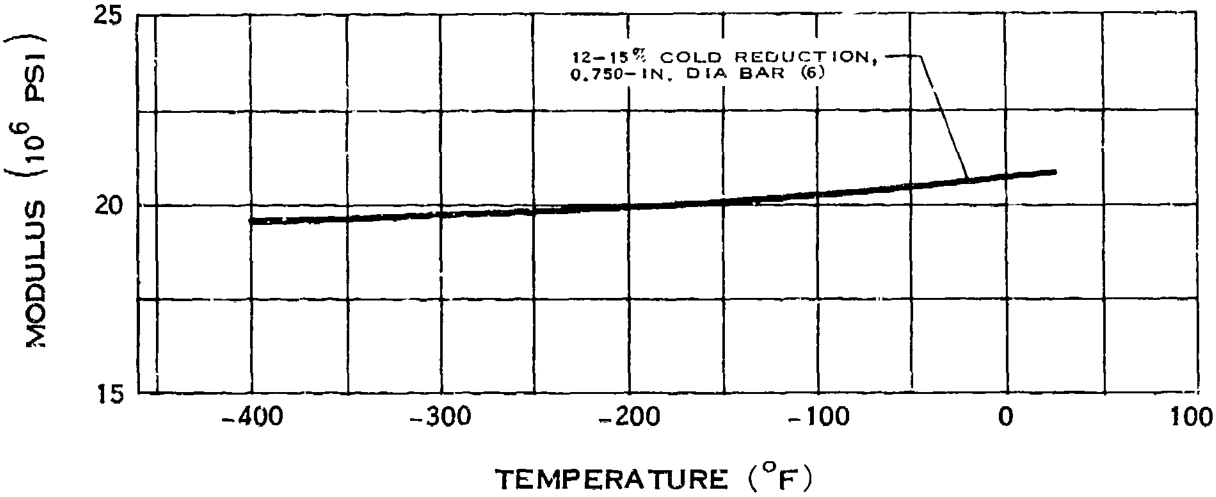


REDUCTION OF AREA OF INVAR

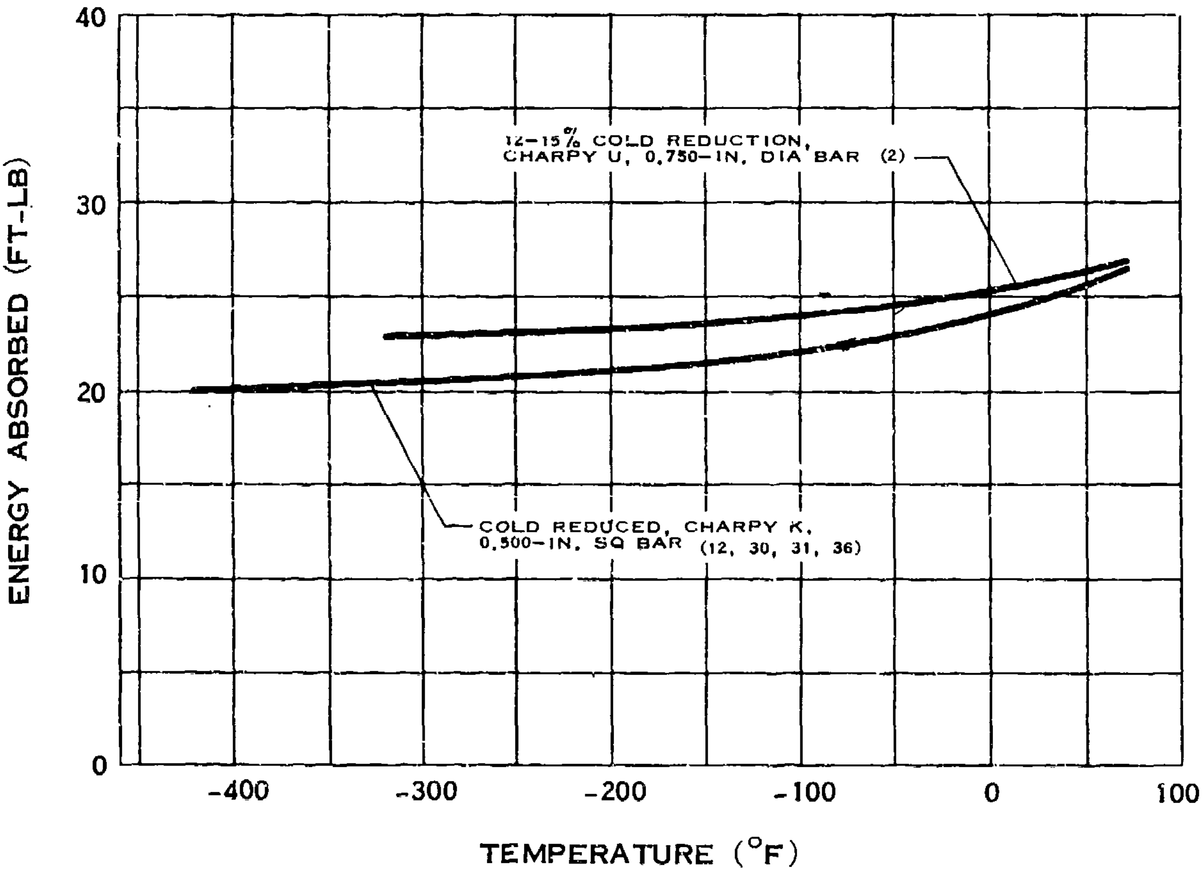
(7–64)



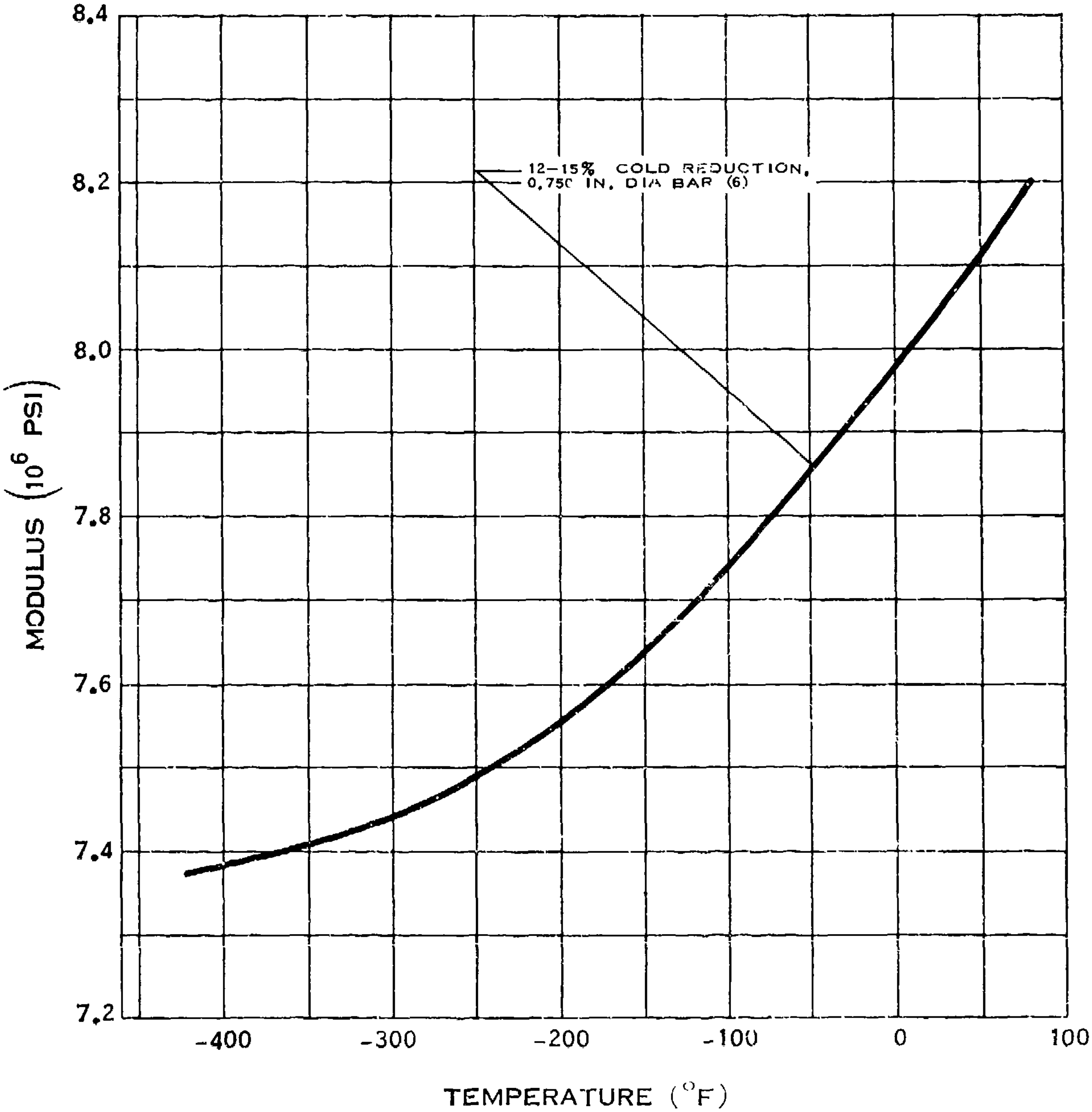
STRESS-STRAIN DIAGRAM FOR INVAR



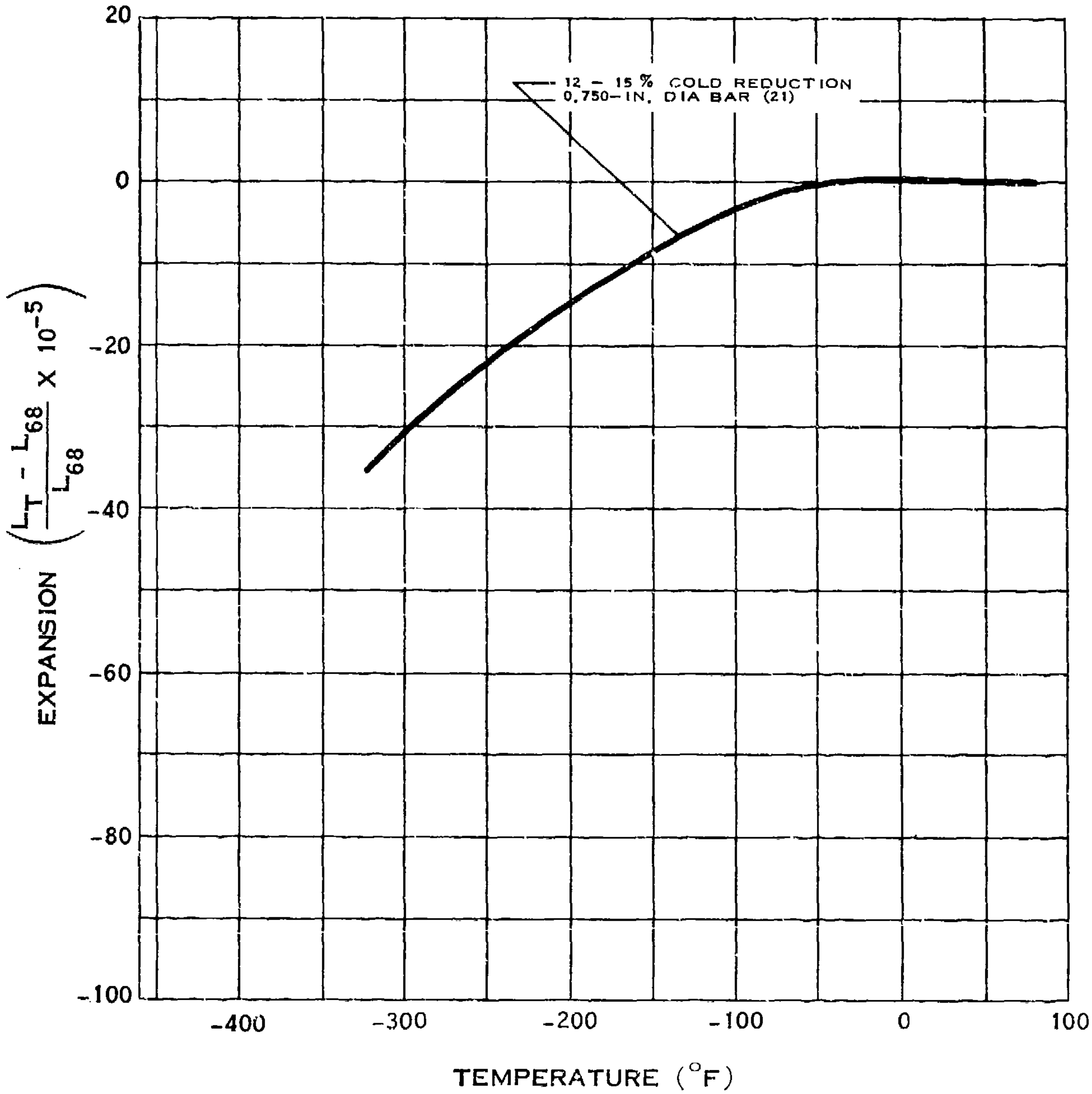
MODULUS OF ELASTICITY OF INVAR



IMPACT STRENGTH OF INVAR

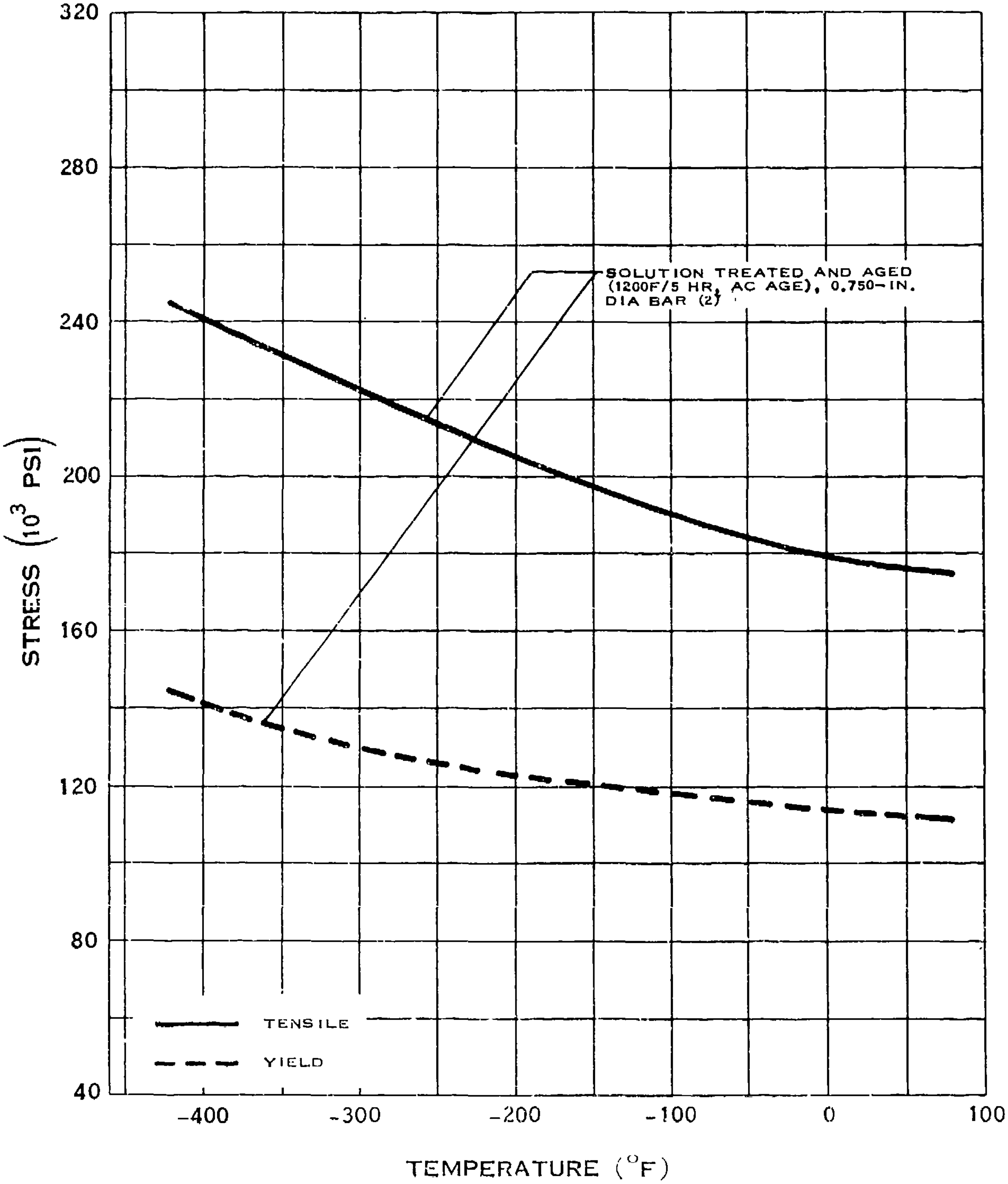


MODULUS OF RIGIDITY OF INVAR

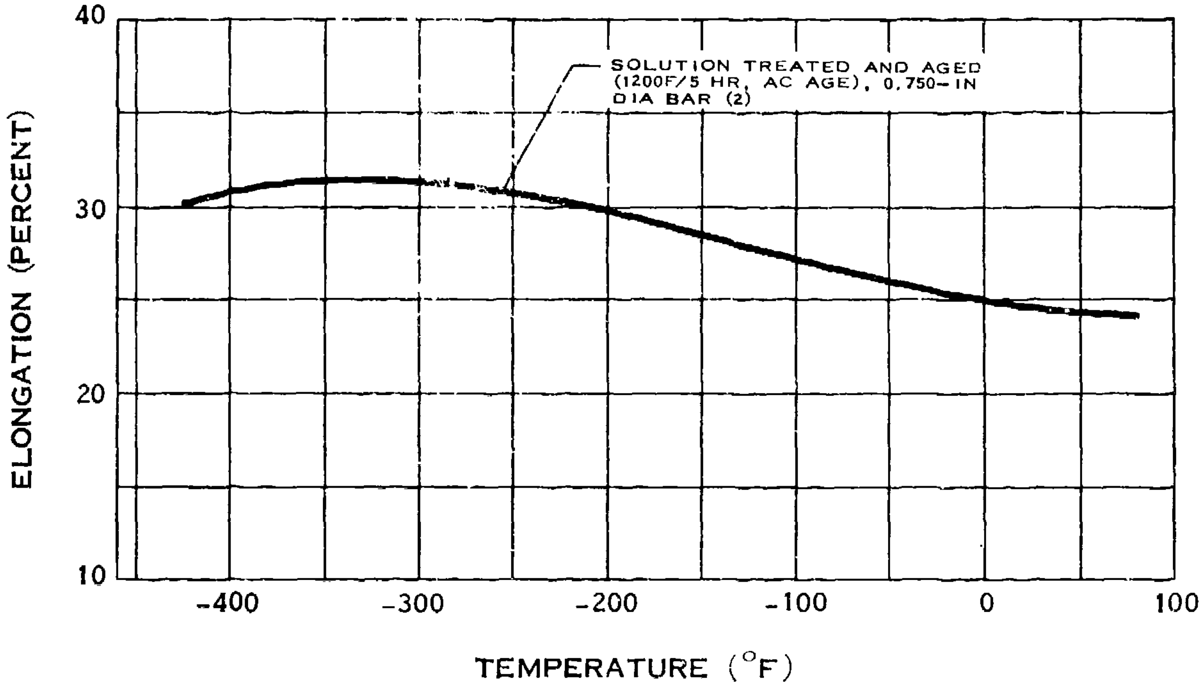


THERMAL EXPANSION OF INVAR

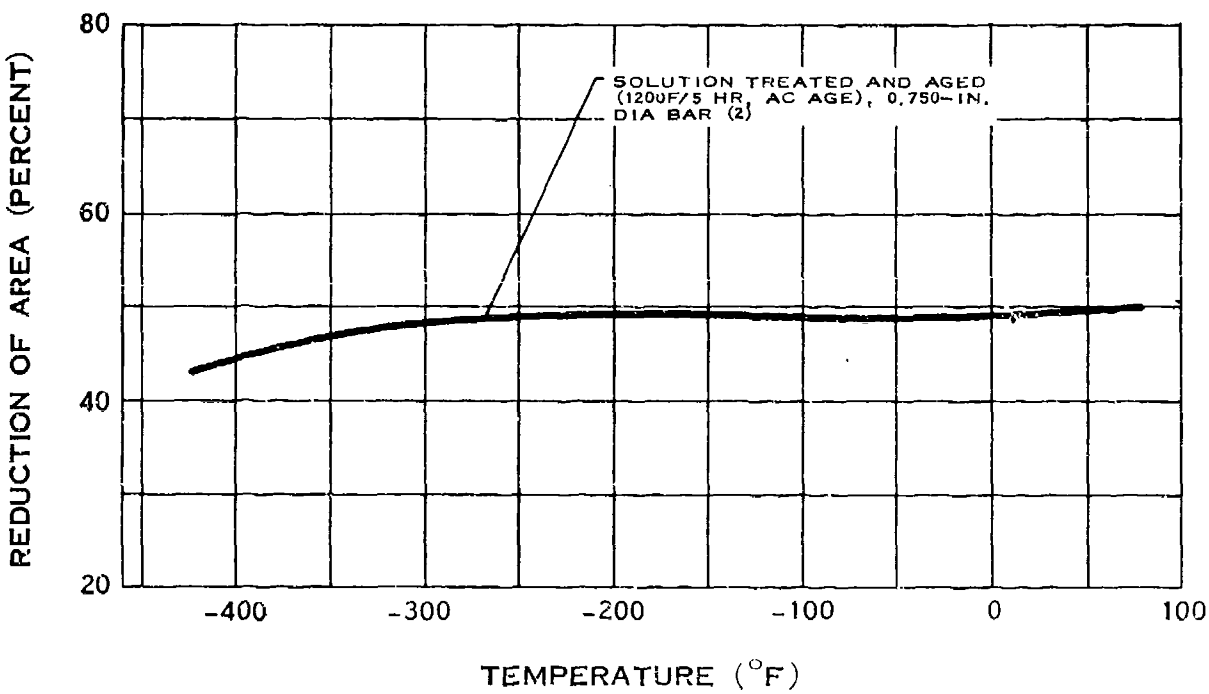
F.6.ab



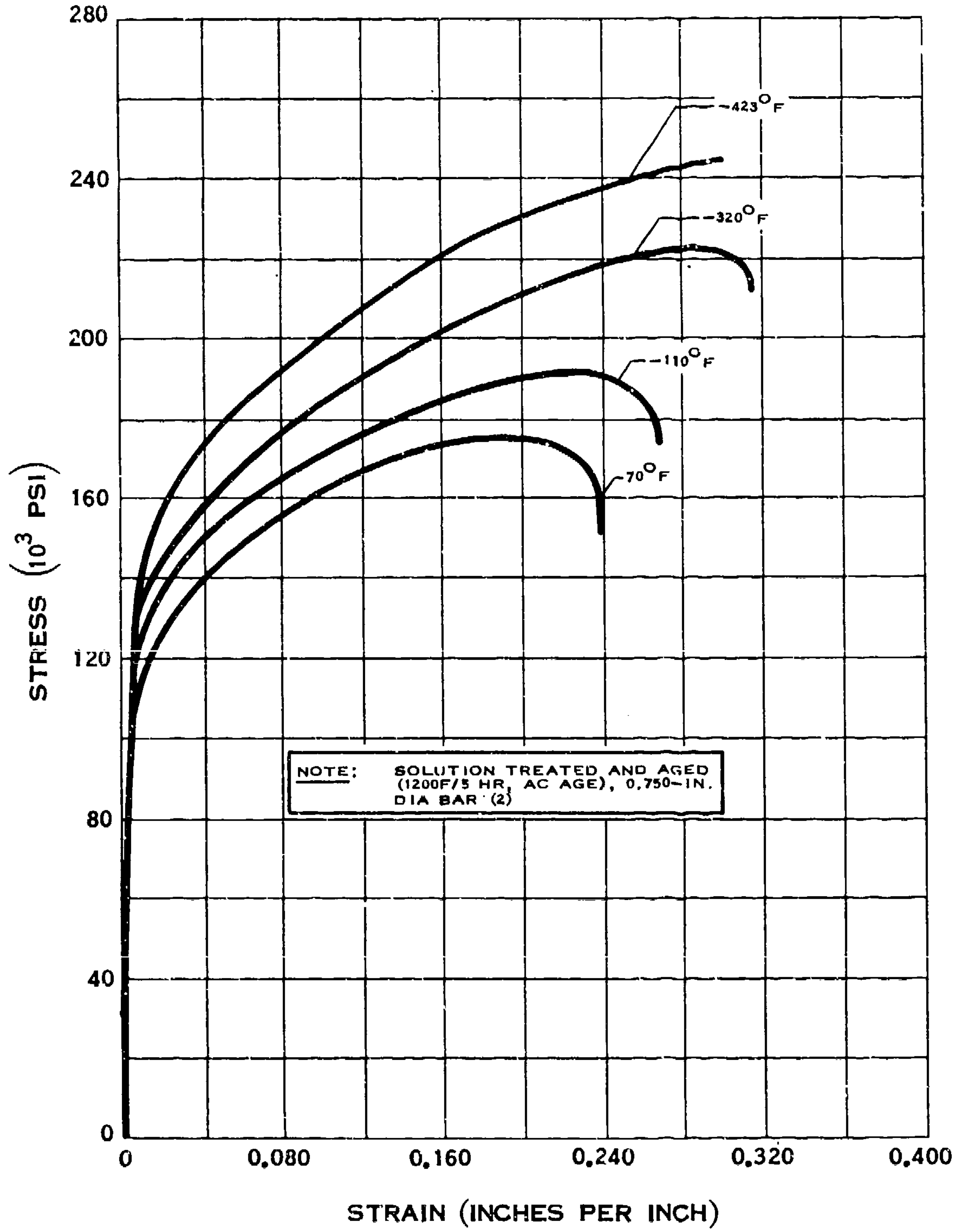
STRENGTH OF NI-SPAN C



ELONGATION OF NI-SPAN C

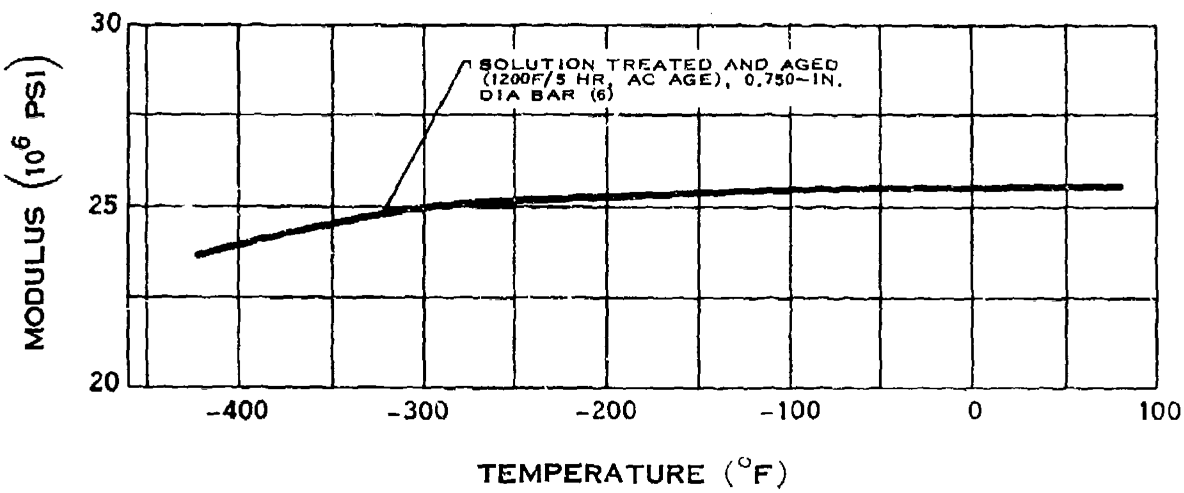


REDUCTION OF AREA OF NI-SPAN C

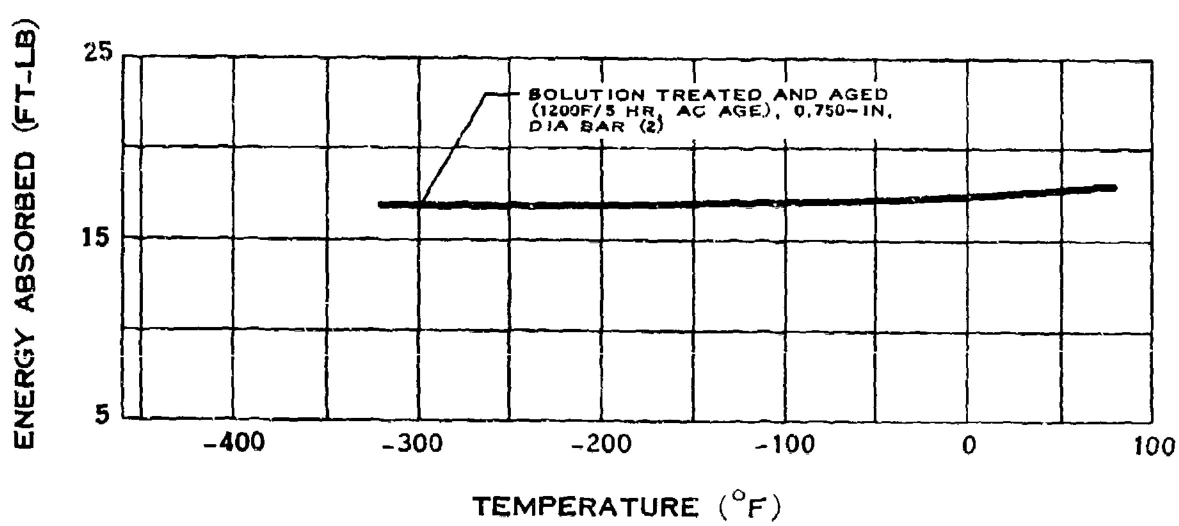


STRESS-STRAIN DIAGRAM FOR NI-SPAN C

F.6.ij



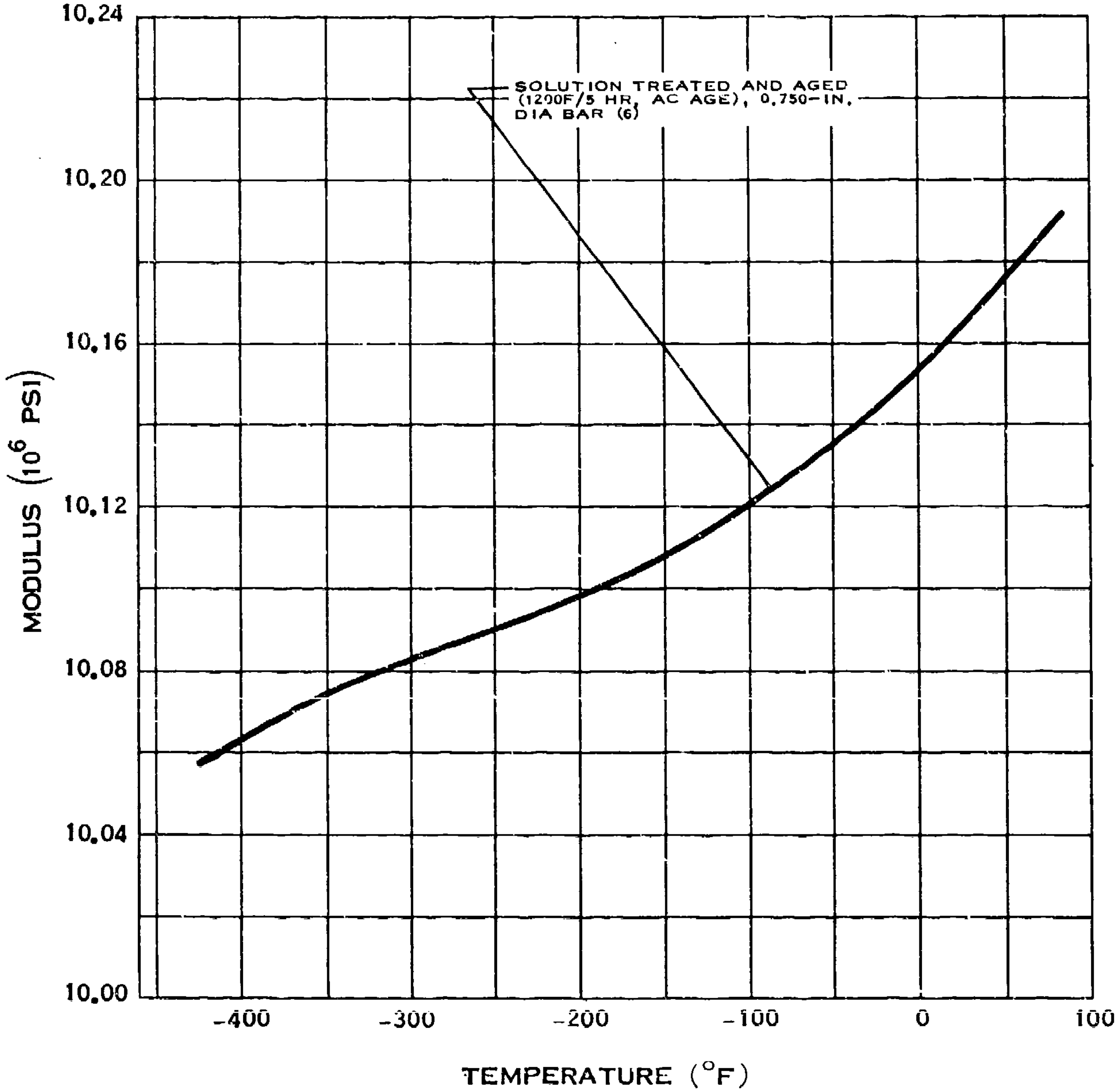
MODULUS OF ELASTICITY OF NI-SPAN C



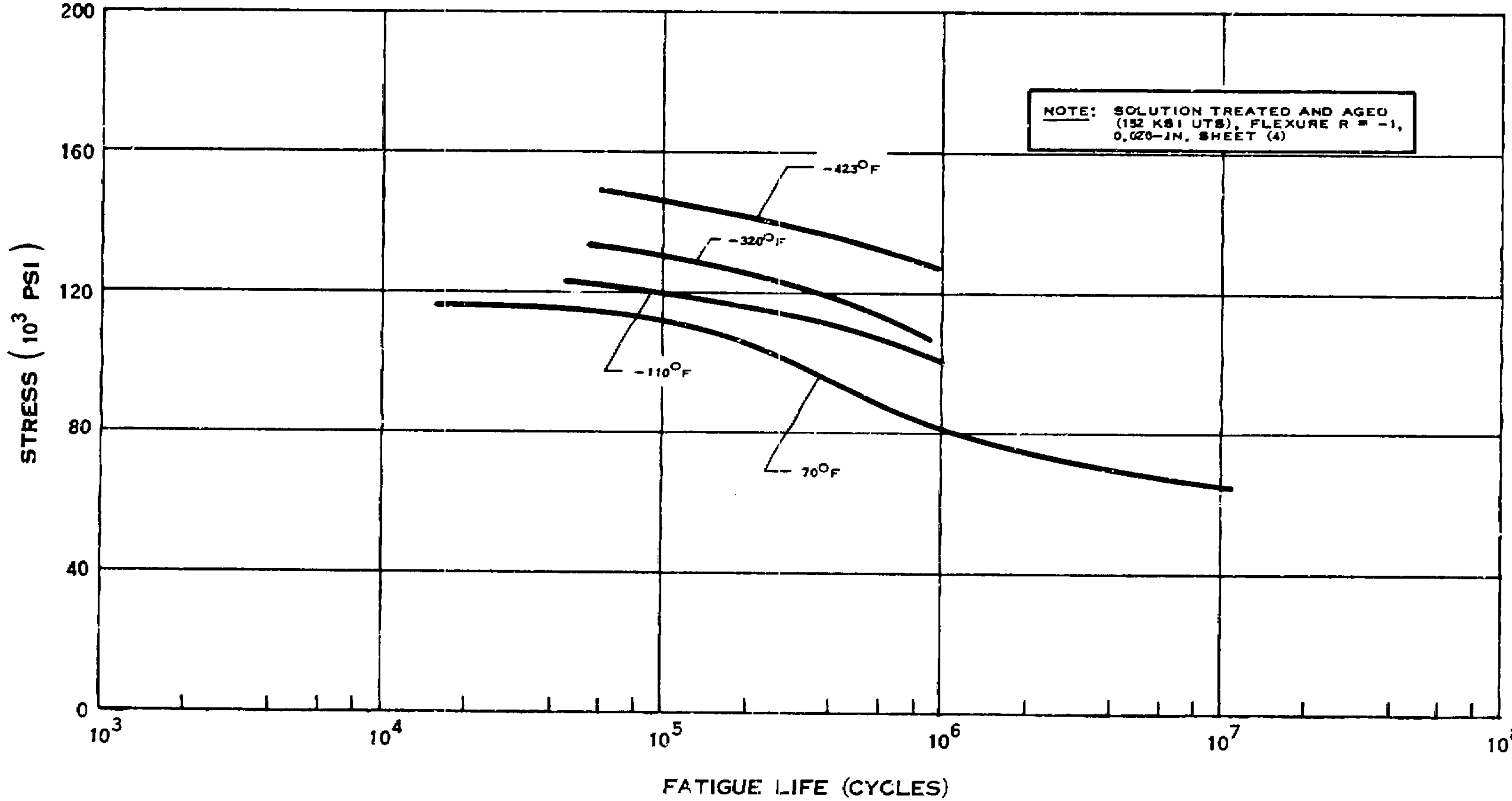
IMPACT STRENGTH OF NI-SPAN C

(7-64)

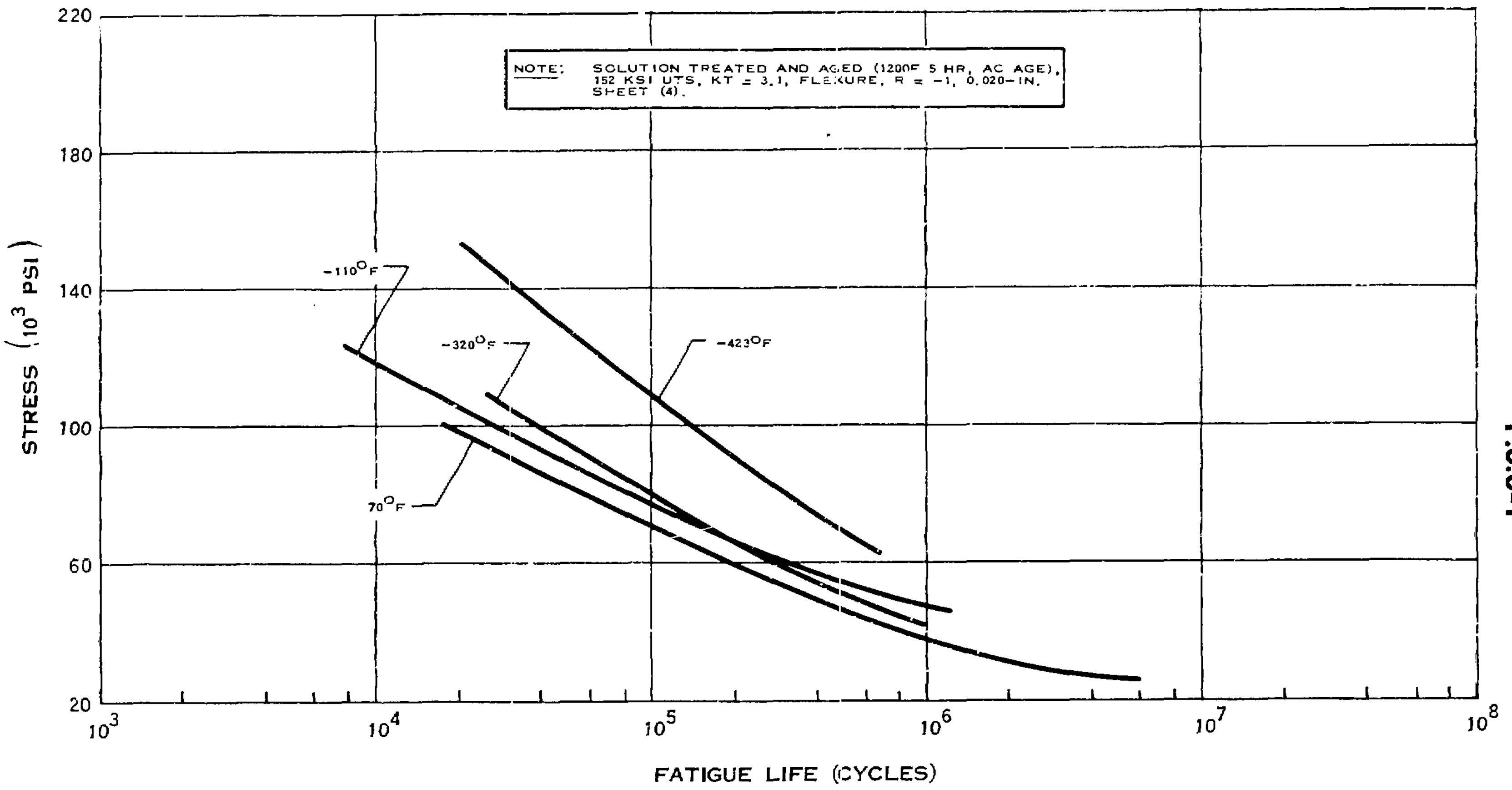
F.6.ℓ



MODULUS OF RIGIDITY OF NI-SPAN C



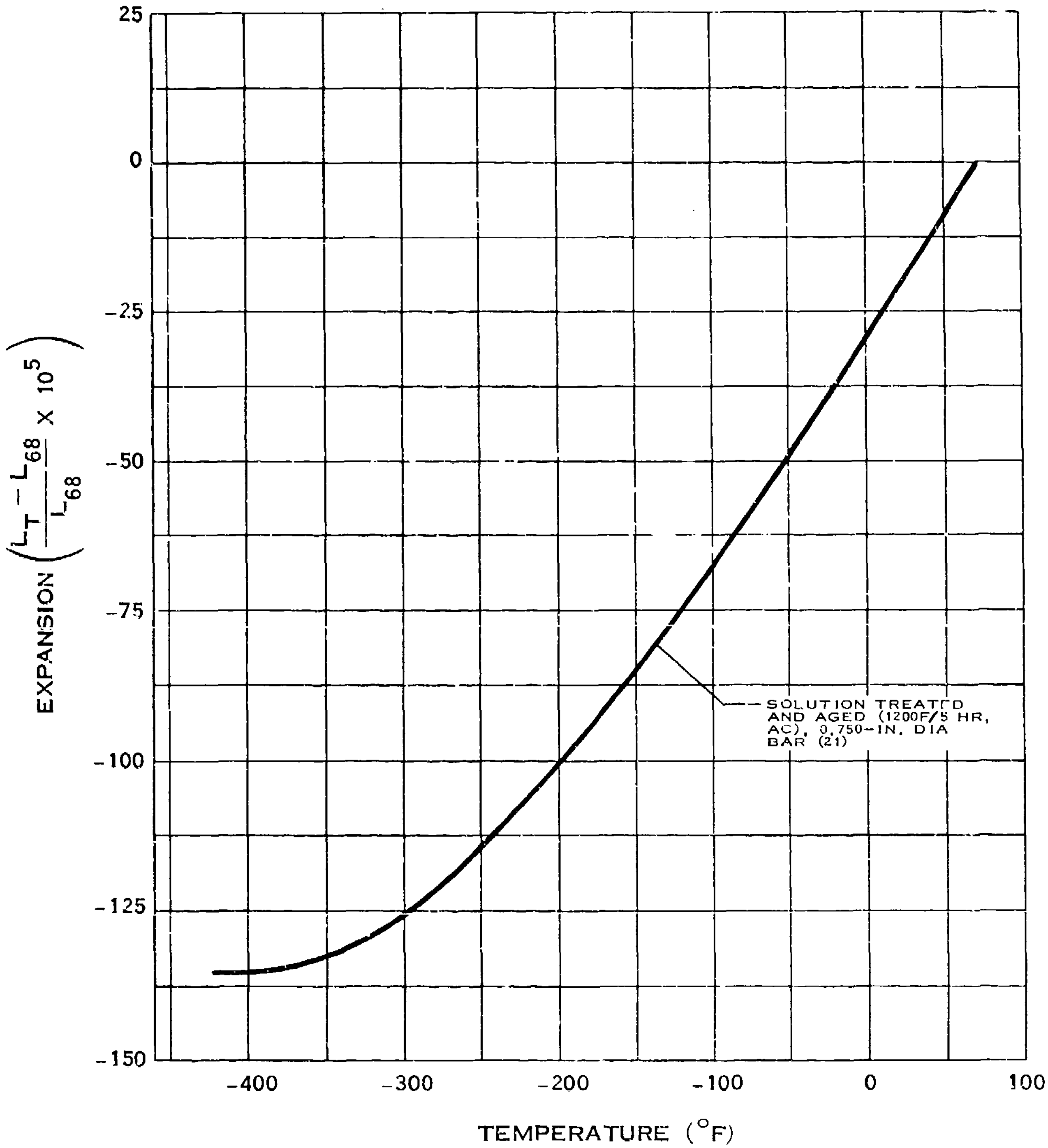
FATIGUE STRENGTH OF NI-SPAN C



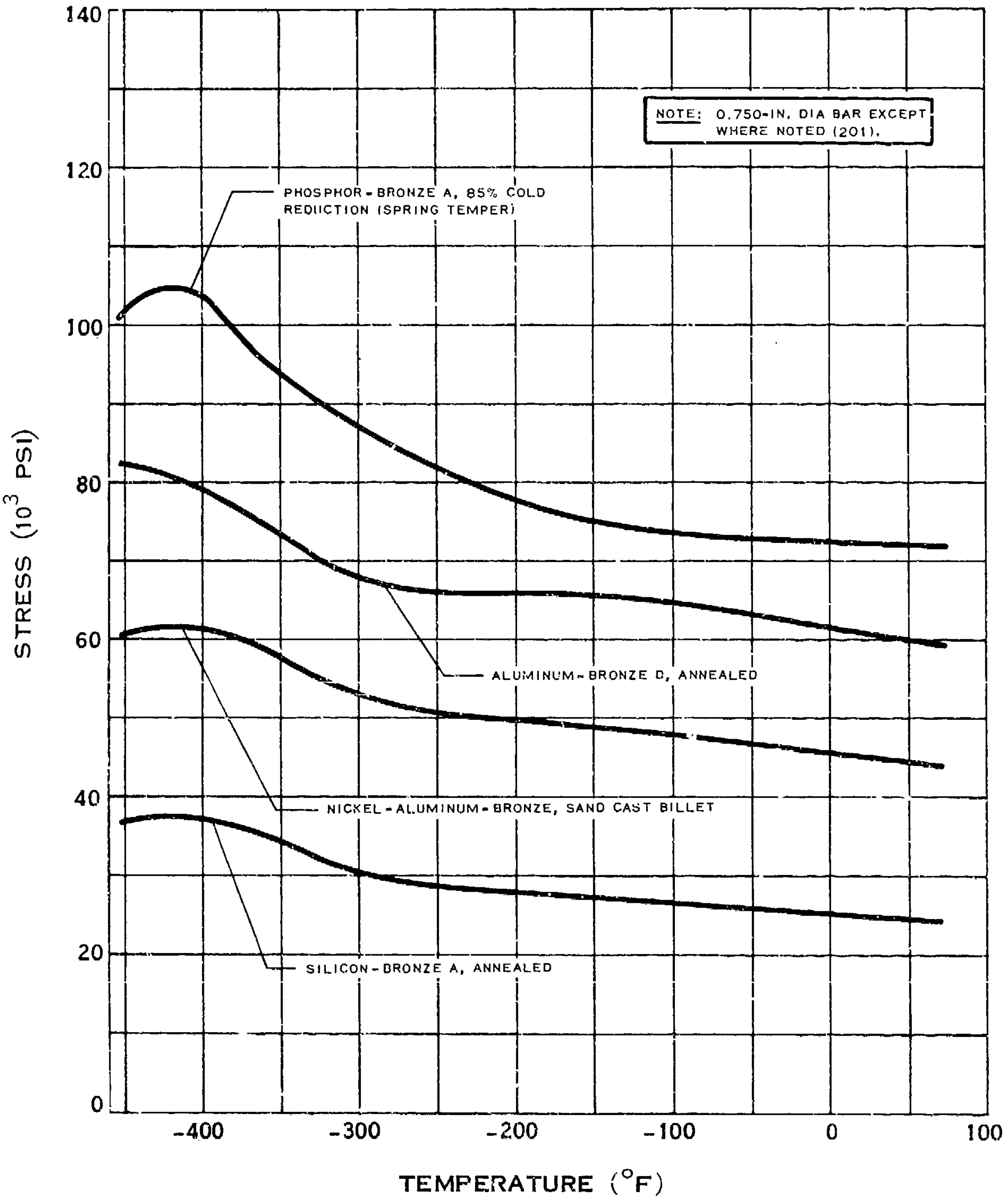
NOTCH FATIGUE STRENGTH OF NI-SPAN C

(7-64)

F.6.t

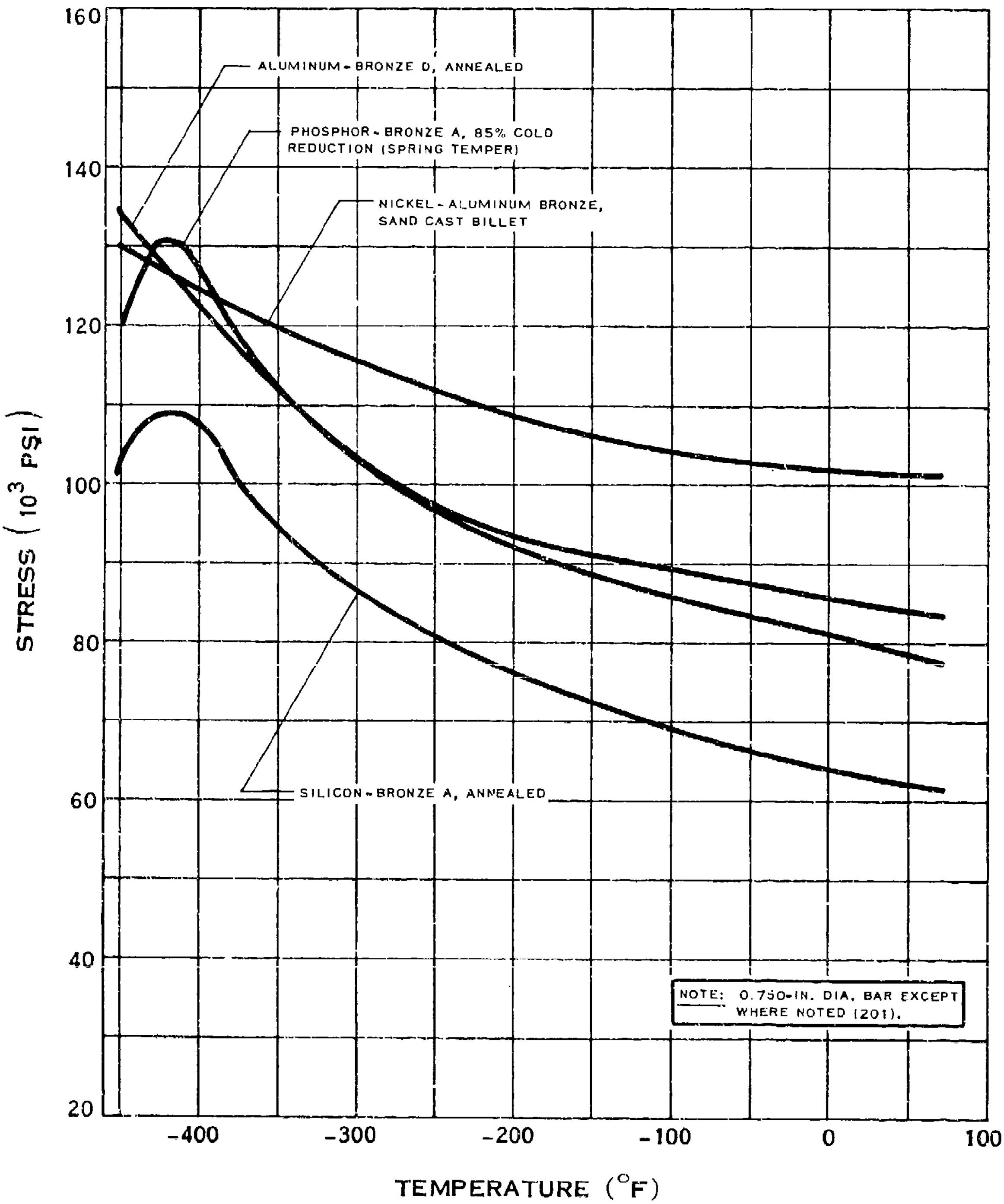


THERMAL EXPANSION OF NI-SPAN C



YIELD STRENGTH OF BRONZE

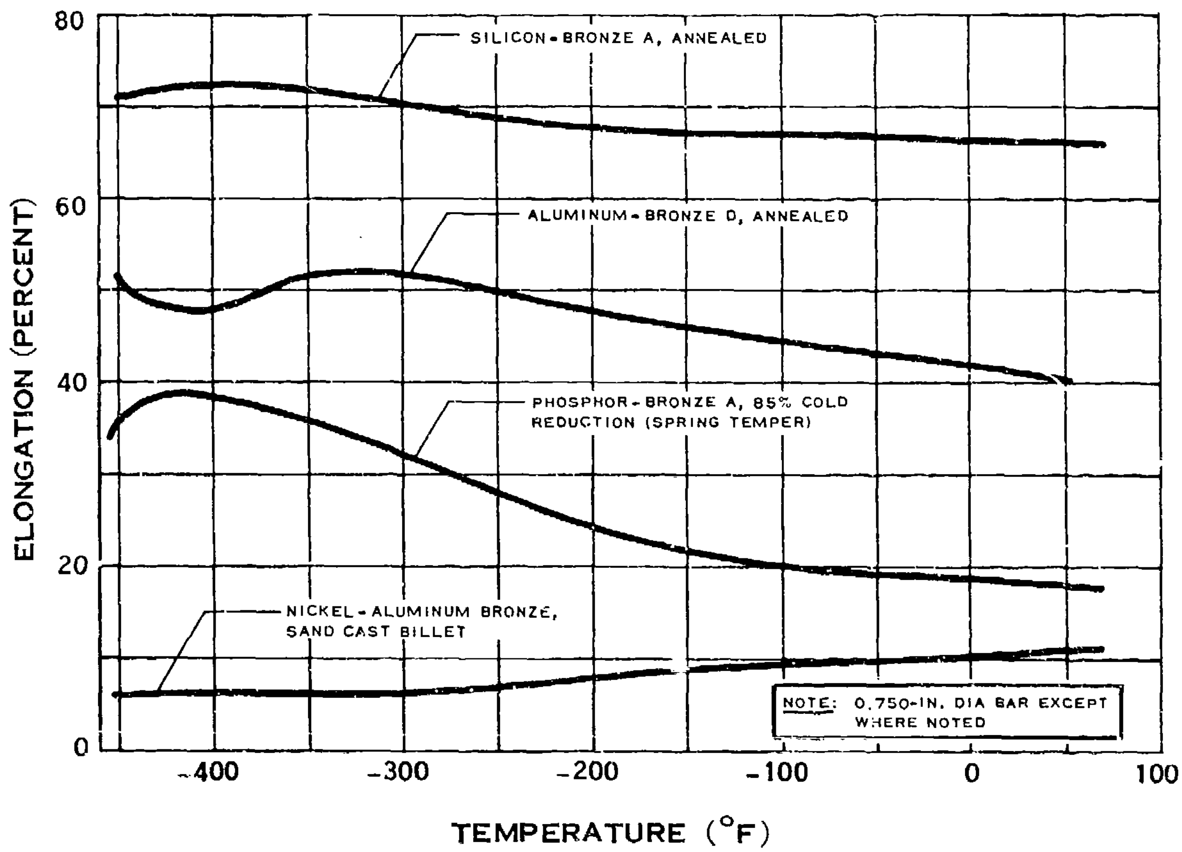
(6-68)



TENSILE STRENGTH OF BRONZE

(6-68)

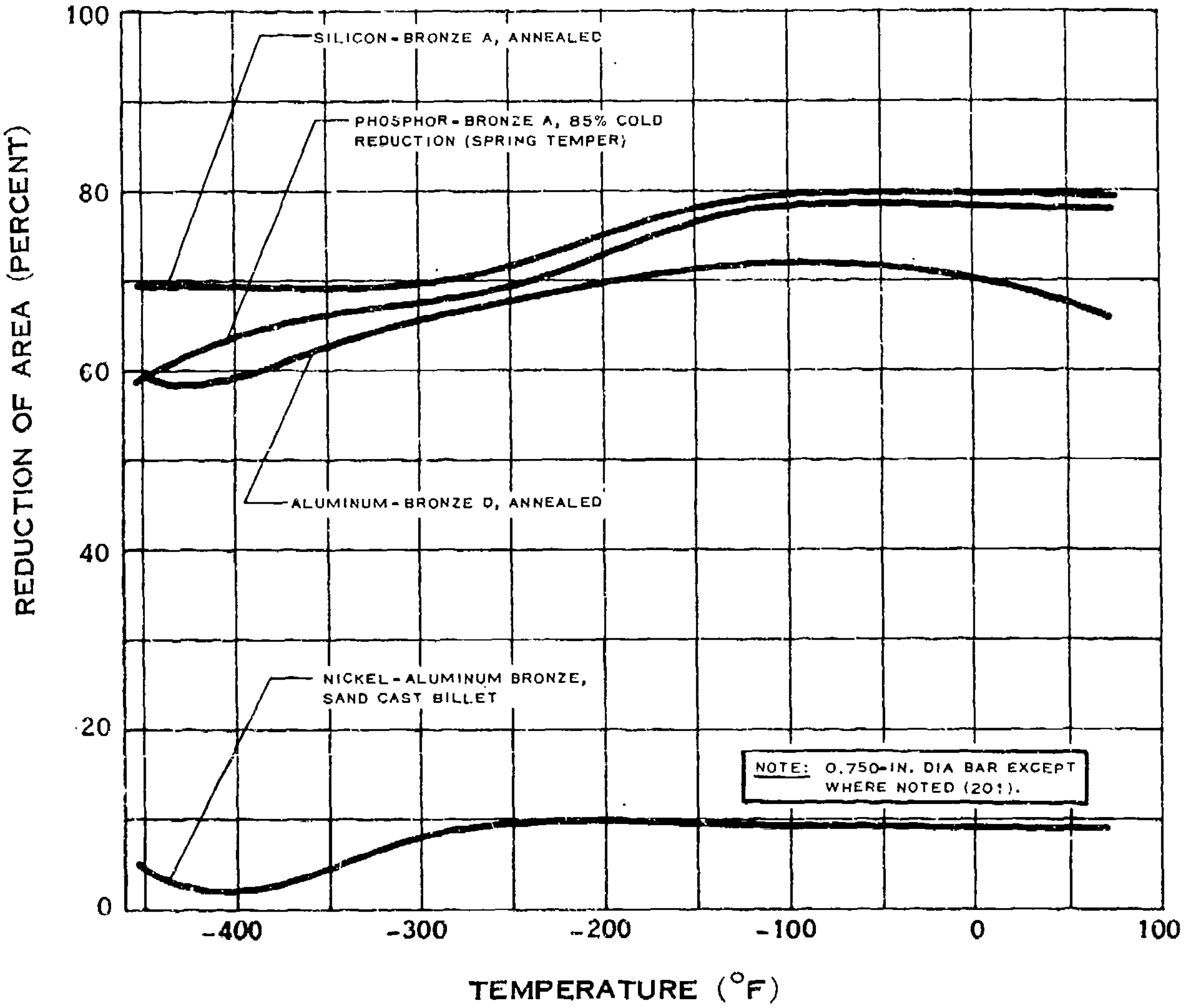
F.7.c



ELONGATION OF BRONZE

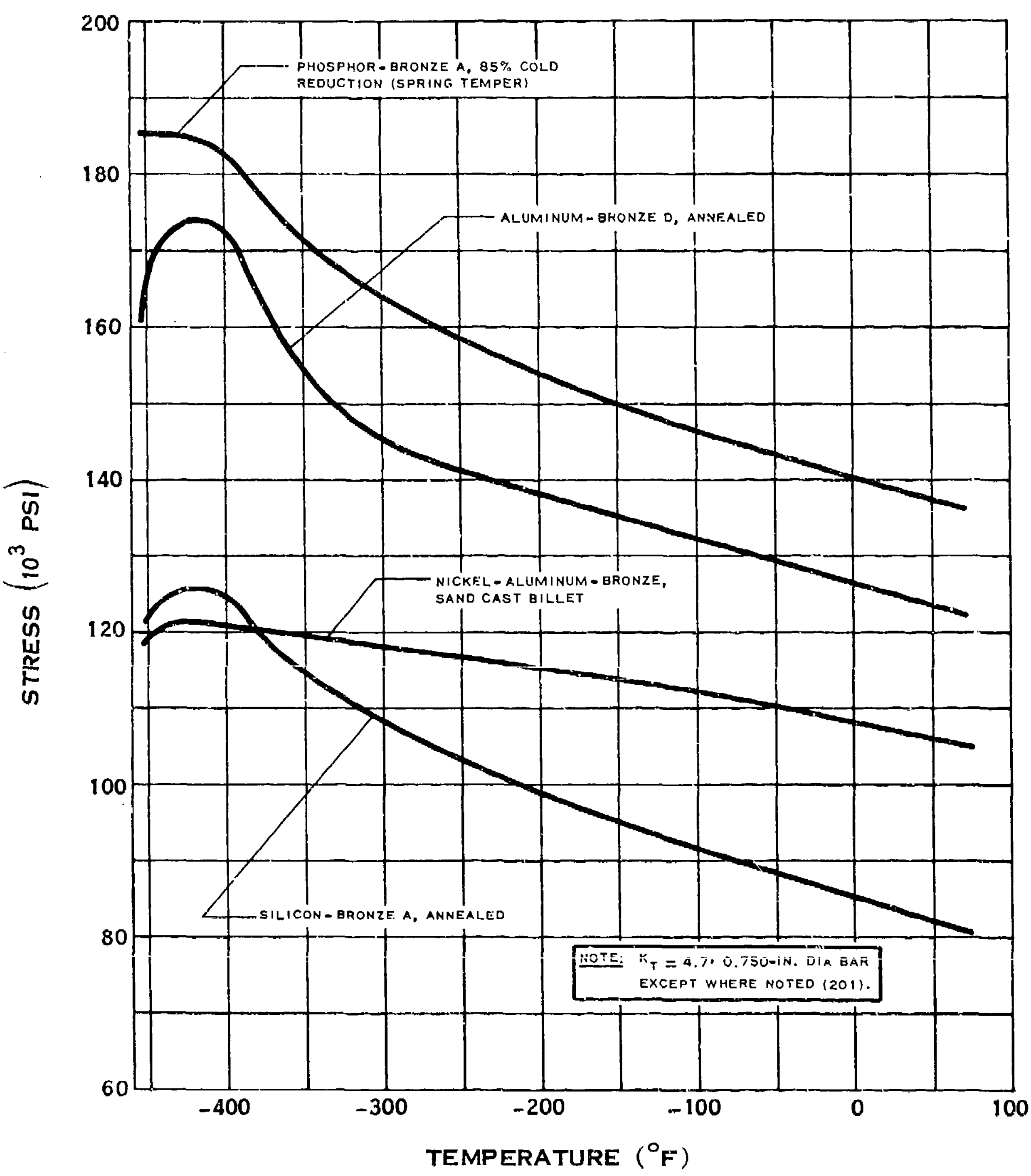
(6-66)

F.7.d



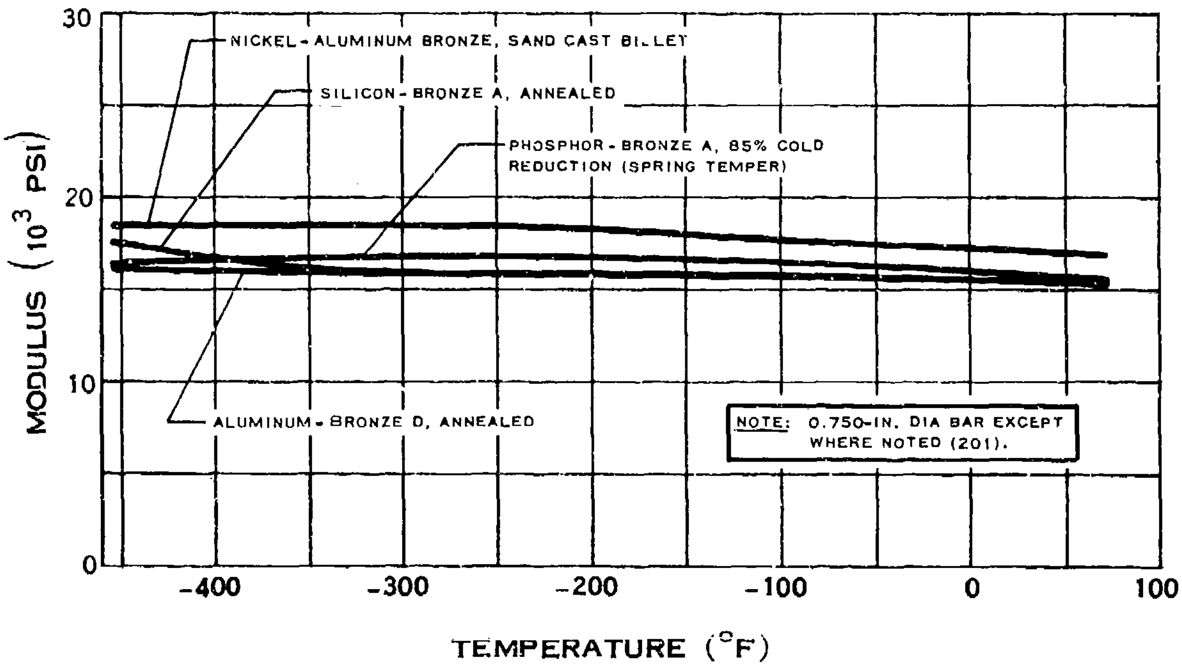
REDUCTION OF AREA OF BRONZE

(6-68)



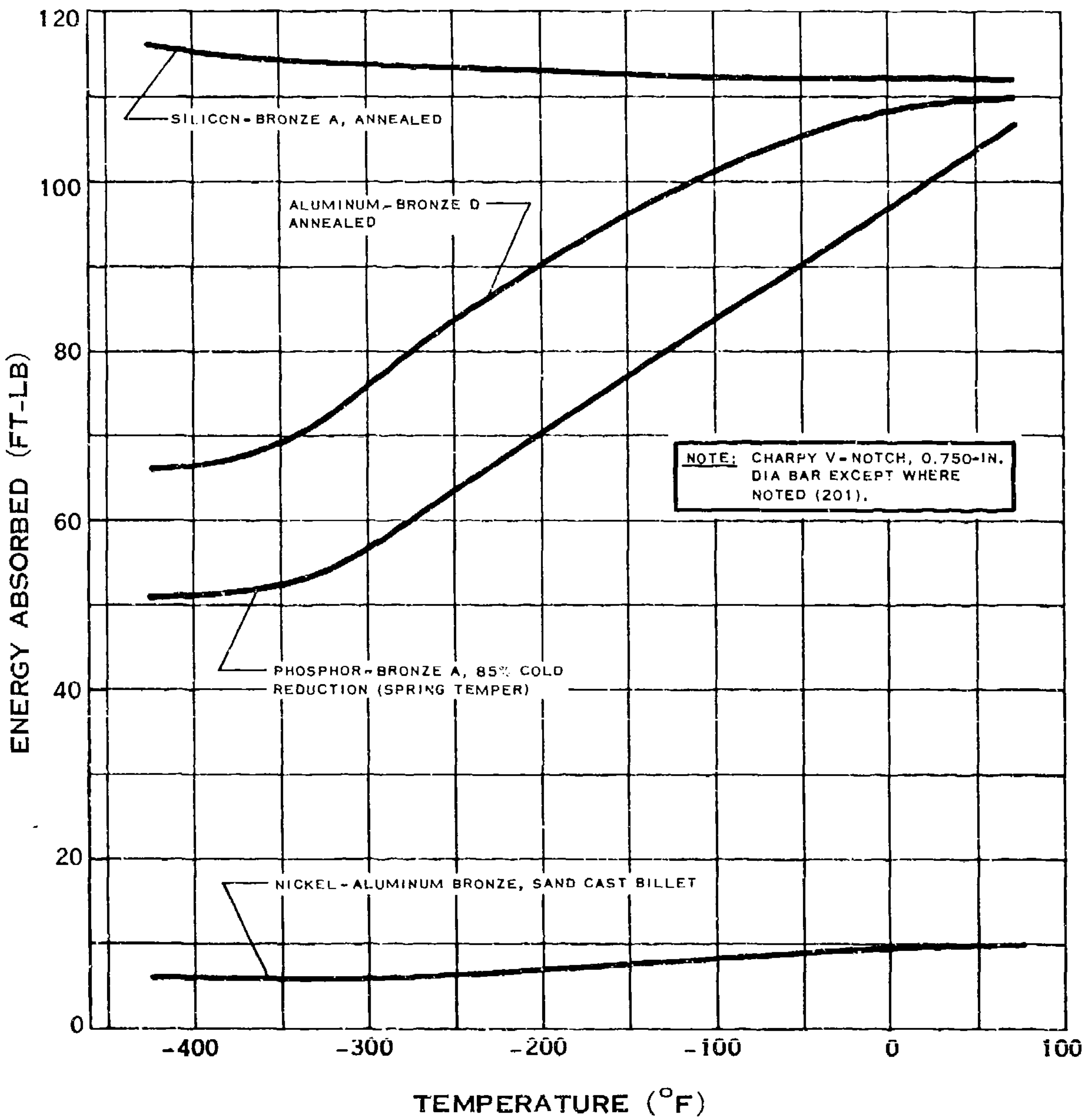
NOTCH TENSILE STRENGTH OF BRONZE

F.7.i



MODULUS OF ELASTICITY OF BRONZE

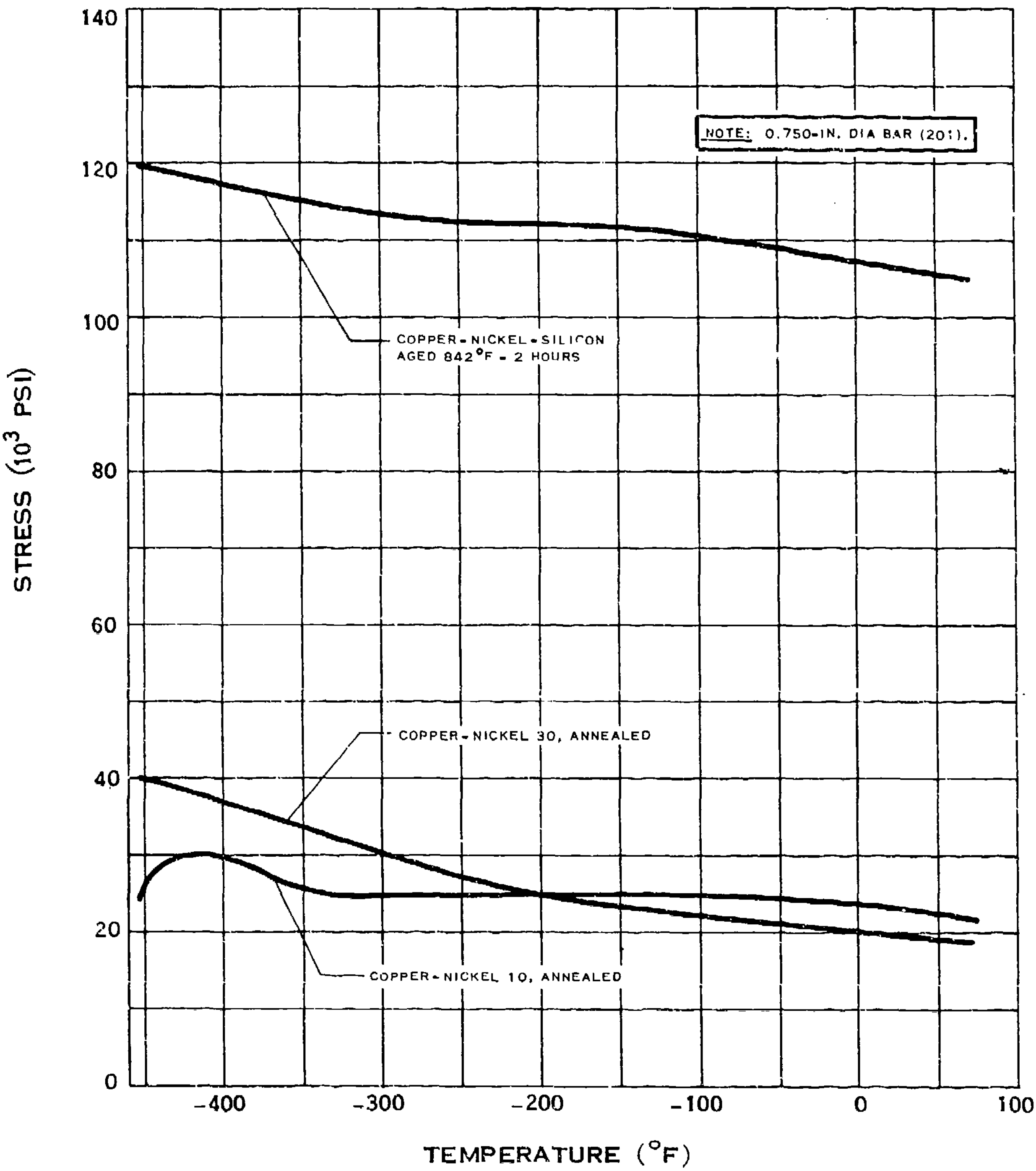
(6-68)



IMPACT STRENGTH OF BRONZE

(6-68)

F.8.a



YIELD STRENGTH OF COPPER-NICKEL

(6-68)

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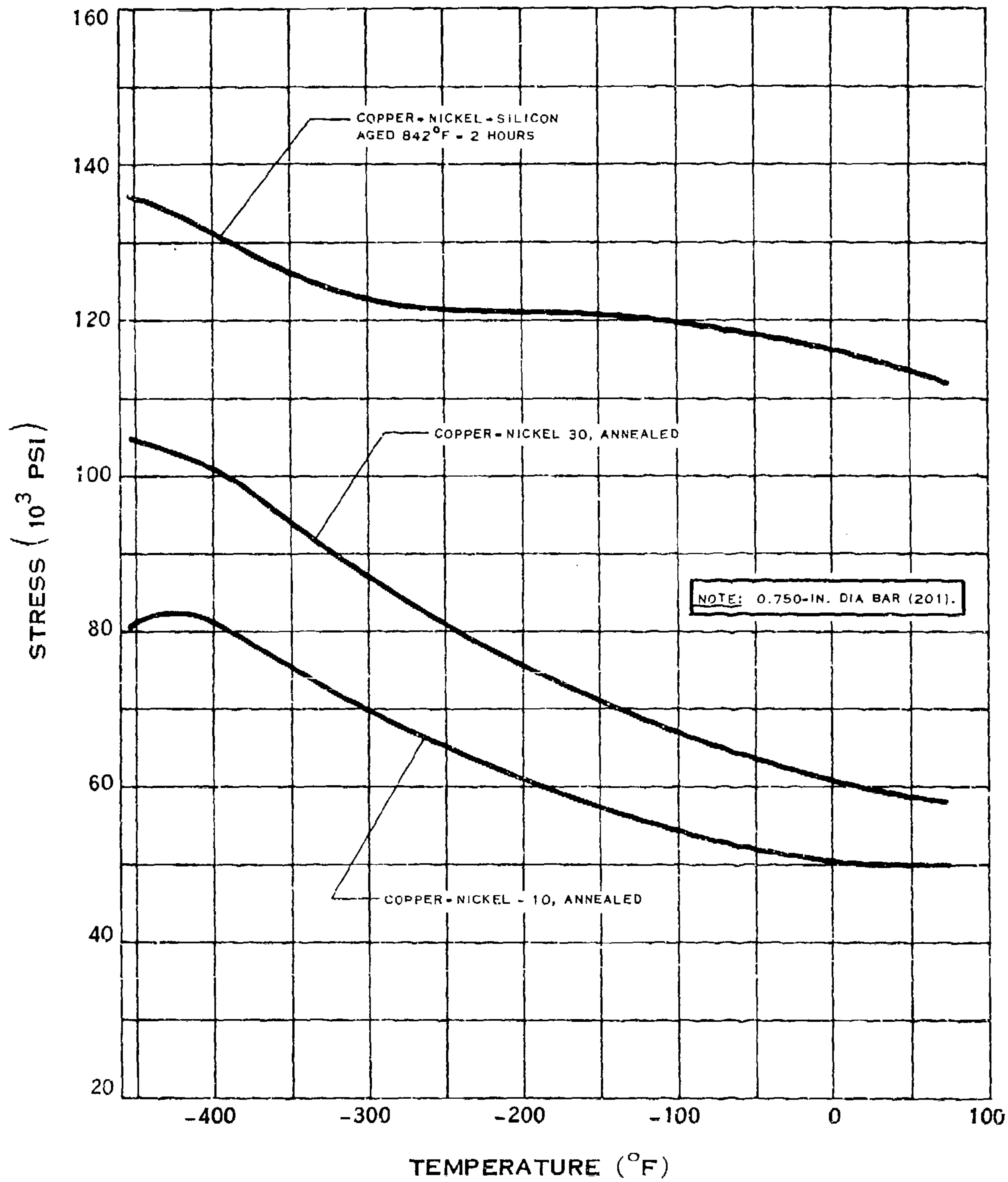
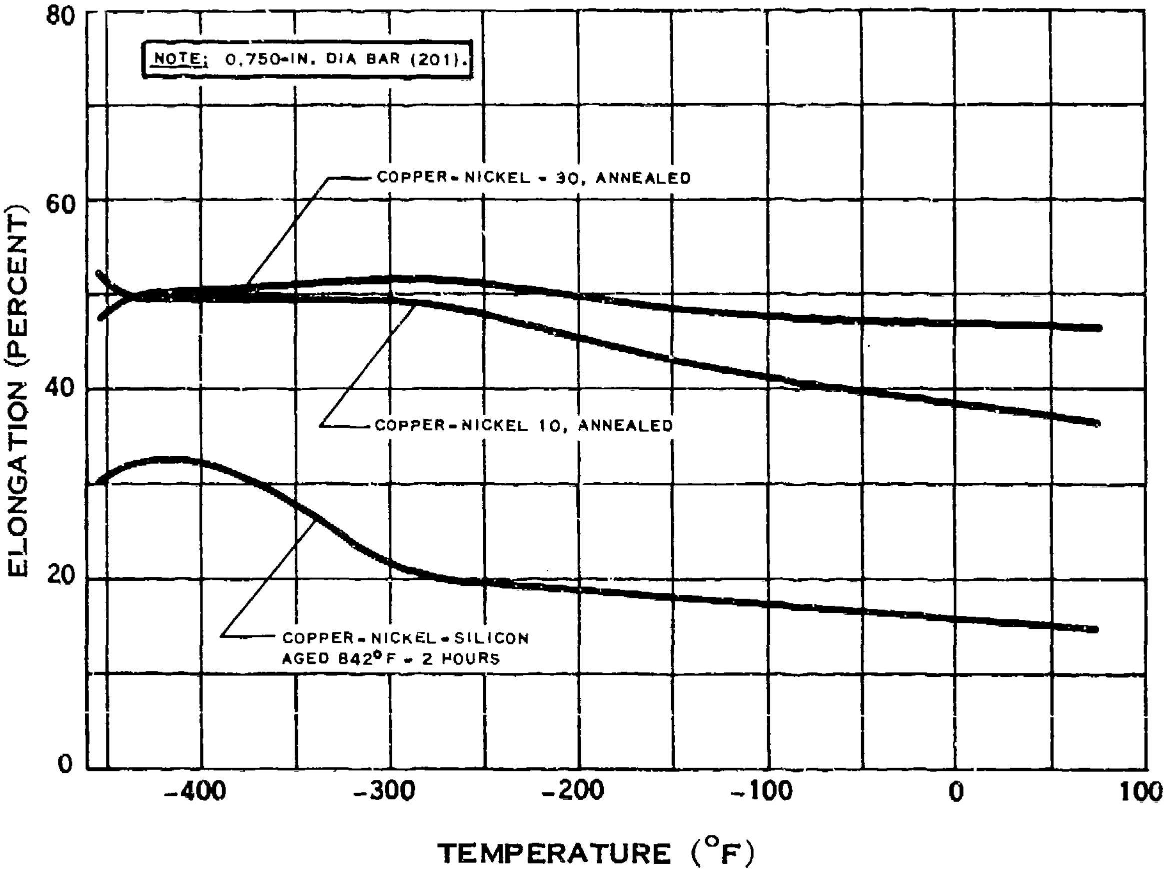


TENSILE STRENGTH OF COPPER-NICKEL

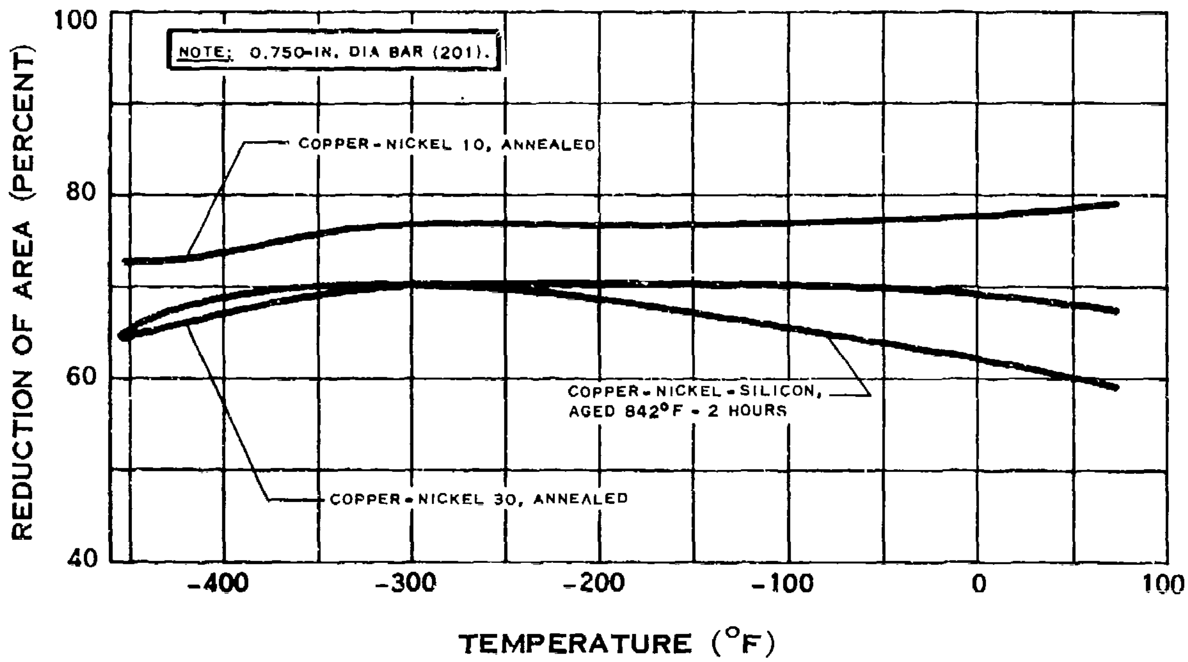
(6-68)



ELONGATION OF COPPER-NICKEL

(6-68)

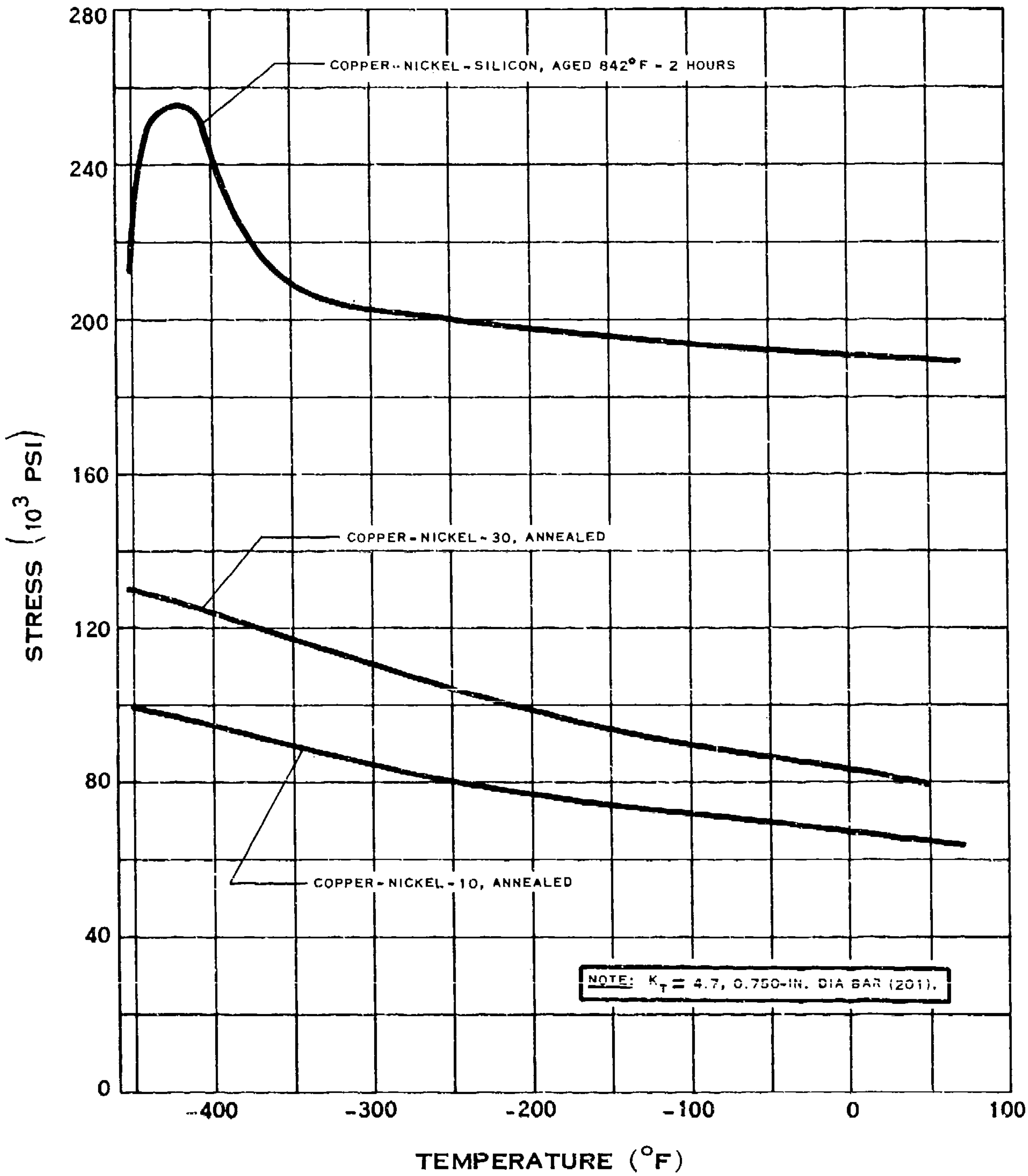
F.8.d



REDUCTION OF AREA OF COPPER – NICKEL

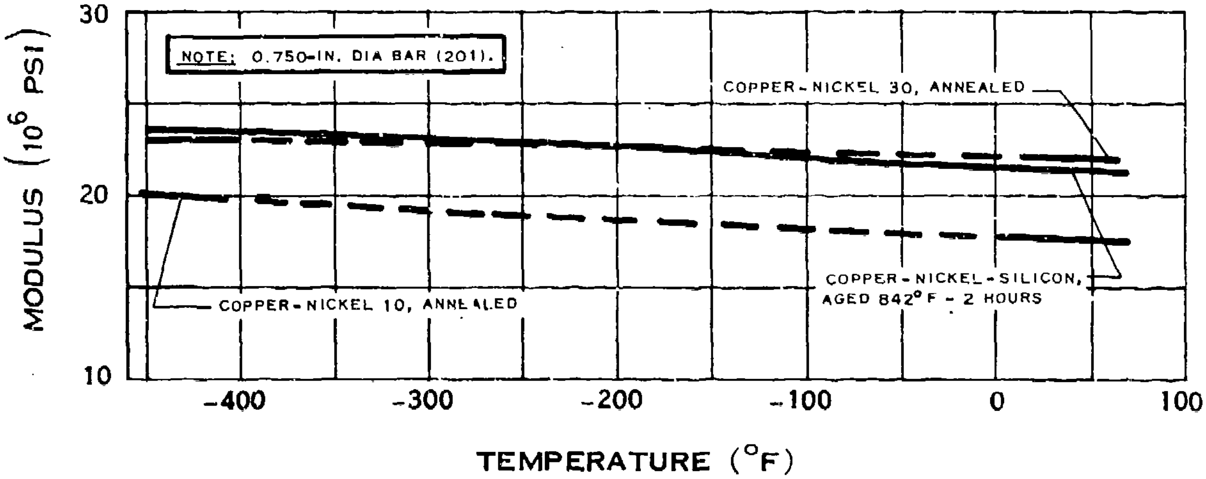
(6-68)

F.8.e

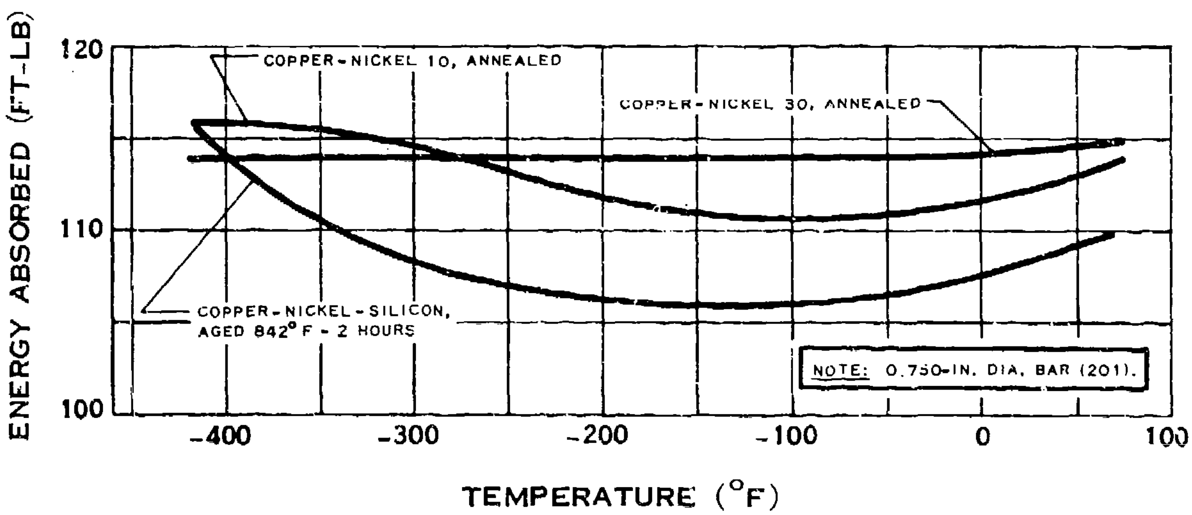


NOTCH TENSILE STRENGTH OF COPPER-NICKEL

(6-68)



MODULUS OF ELASTICITY OF COPPER-NICKEL

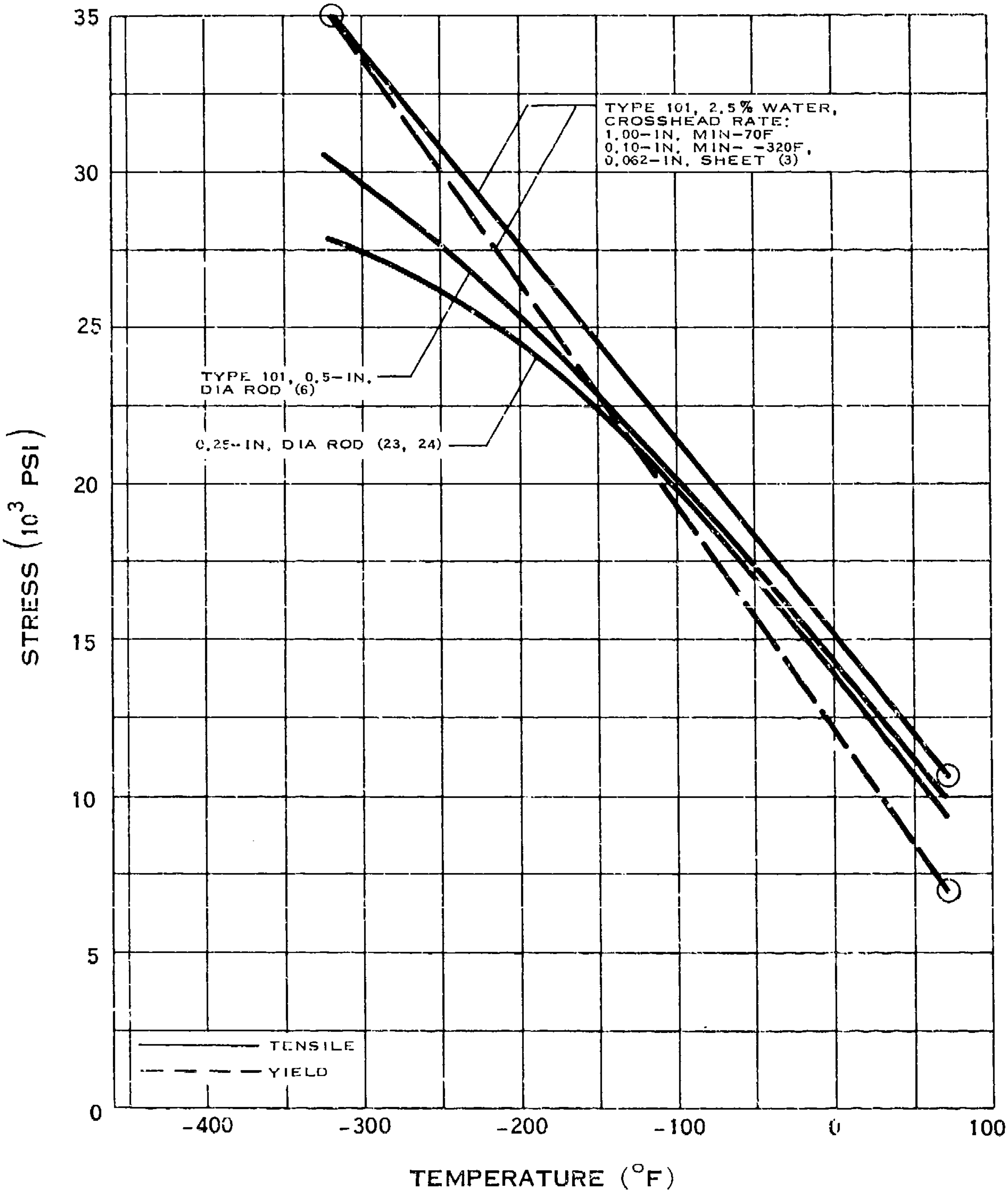


IMPACT STRENGTH OF COPPER-NICKEL

(6-68)

G - POLYMERIC MATERIALS

G.1.ab



STRENGTH OF NYLON

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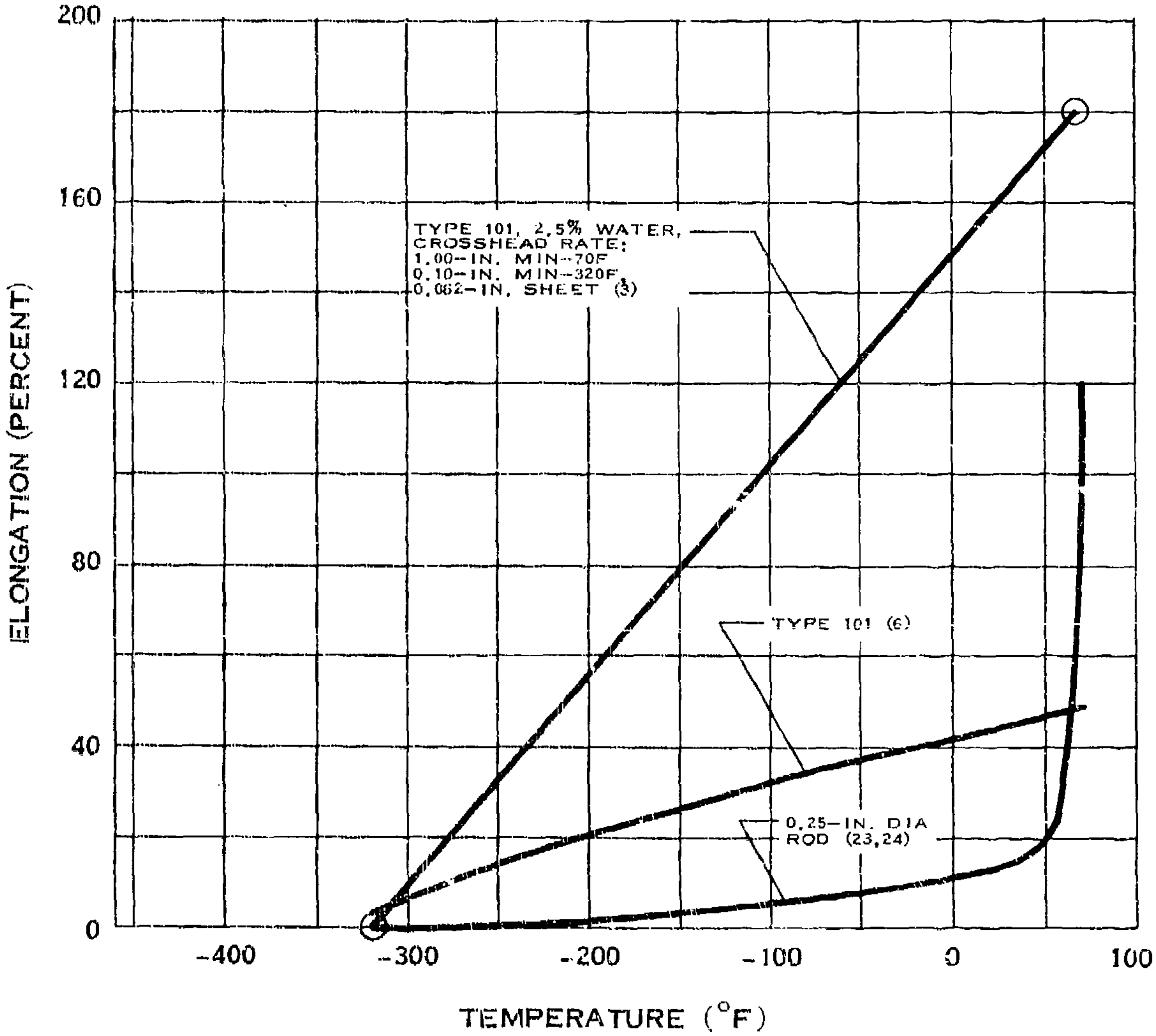
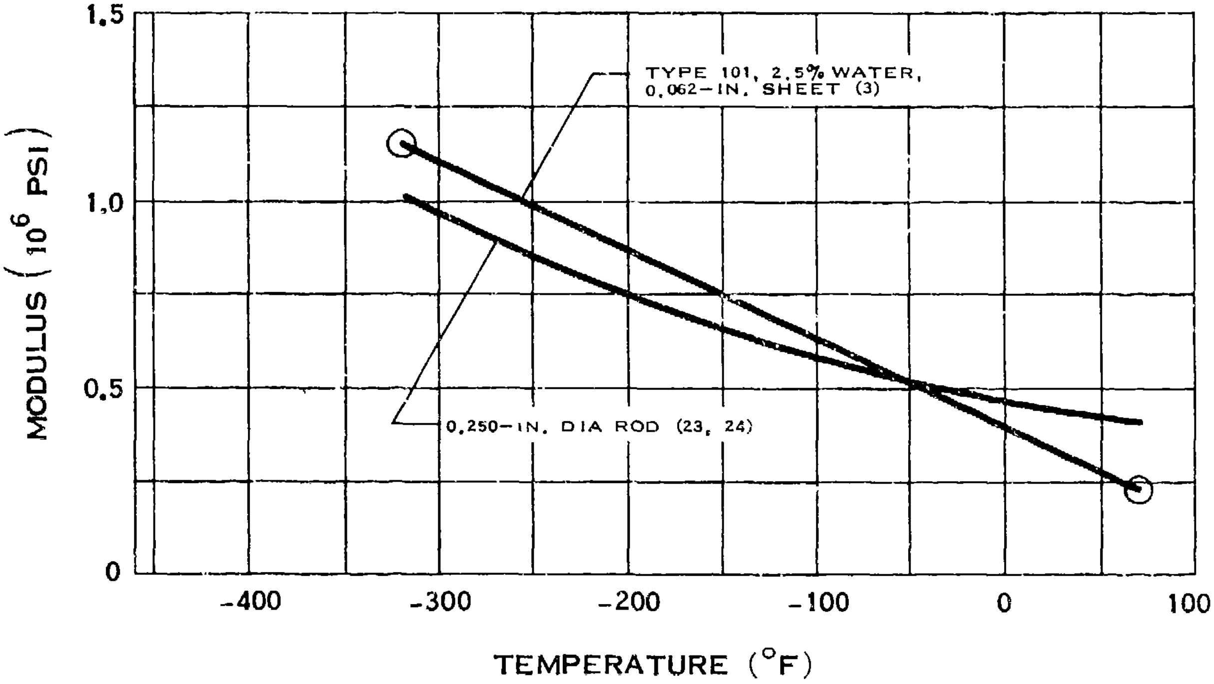
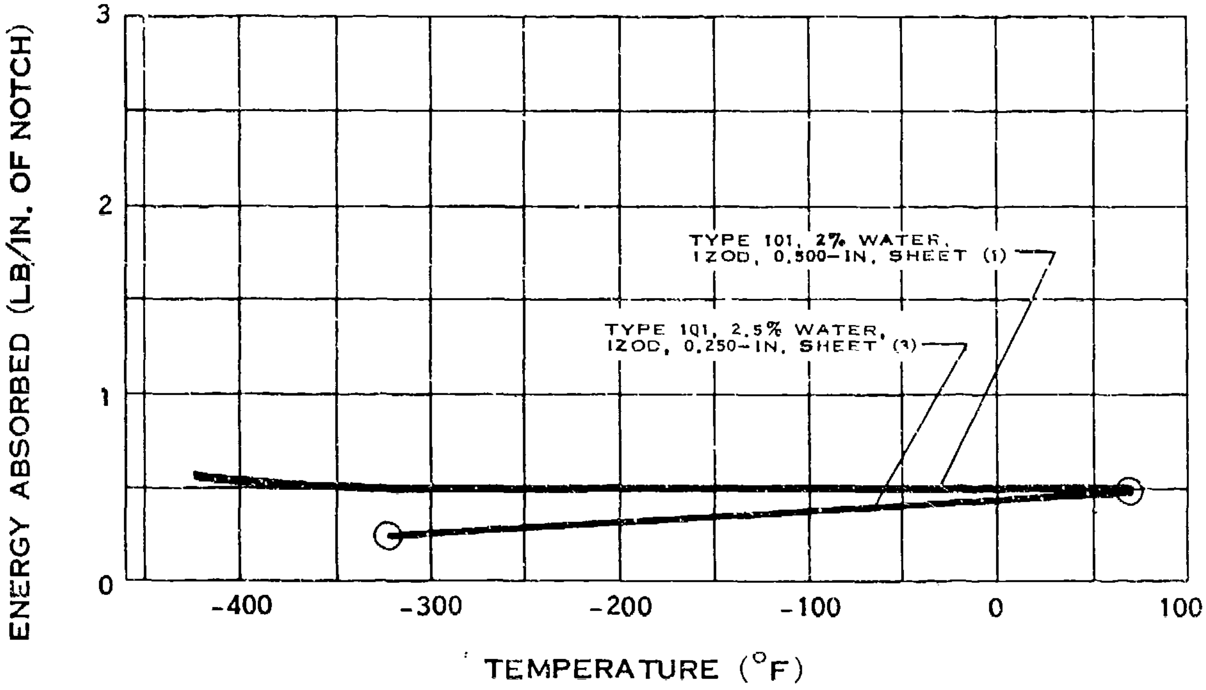


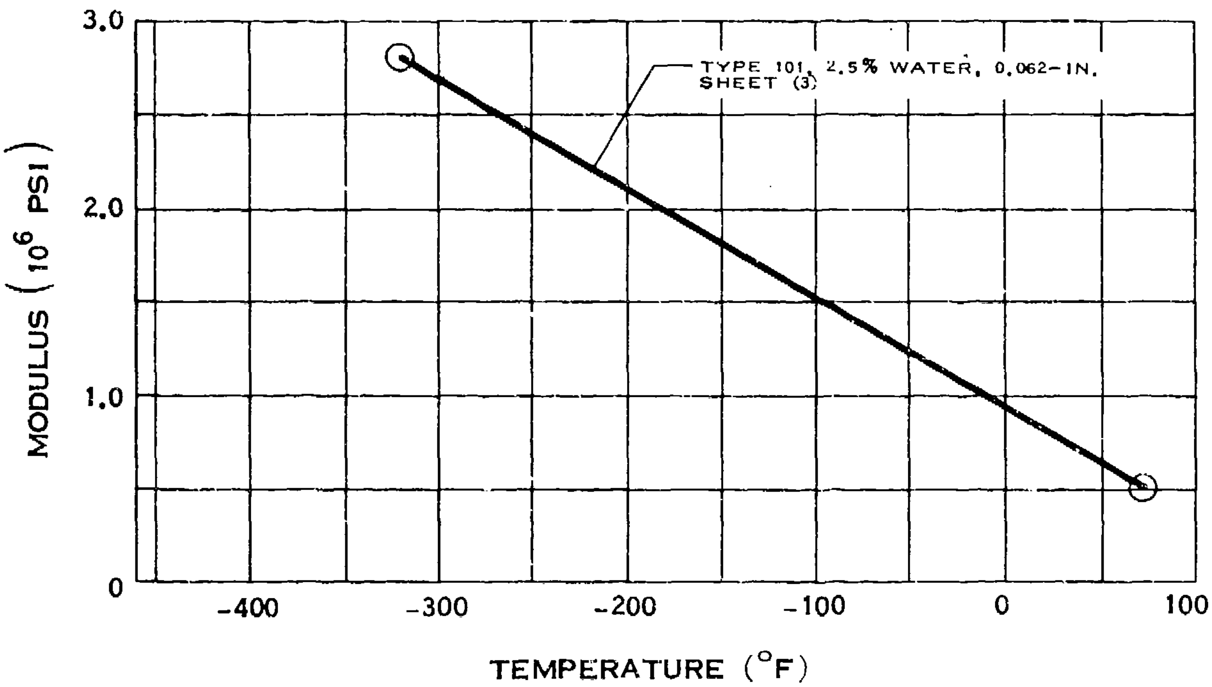
ELONGATION OF NYLON



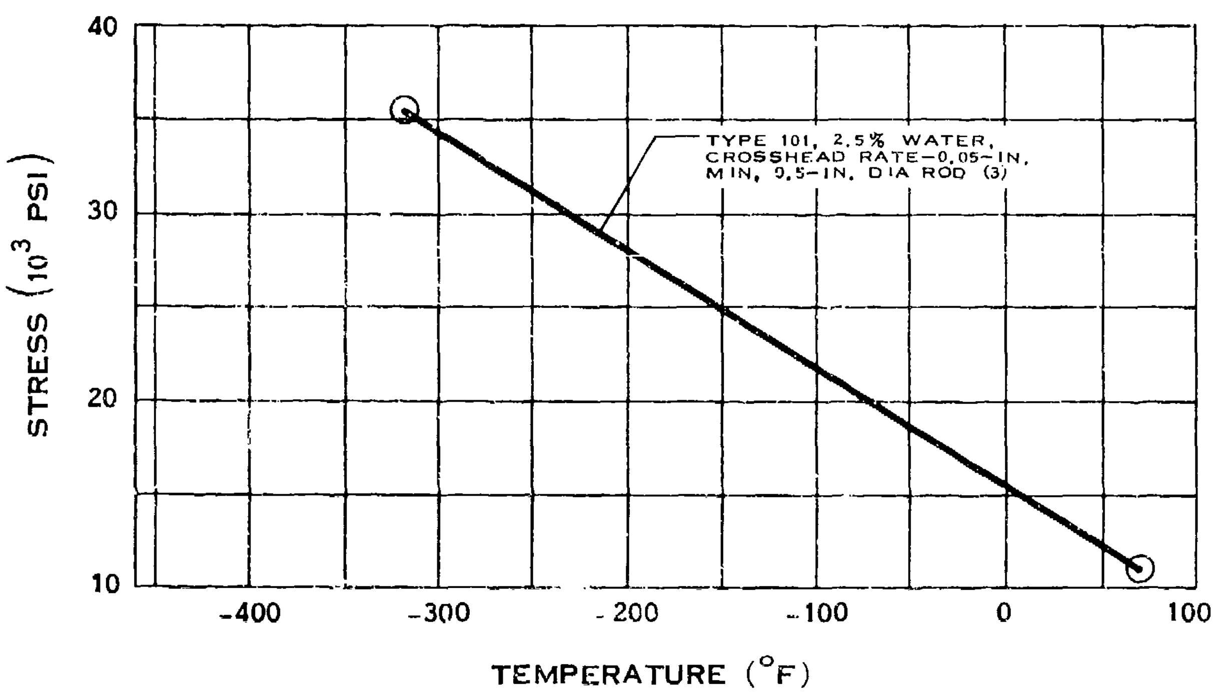
MODULUS OF ELASTICITY OF NYLON



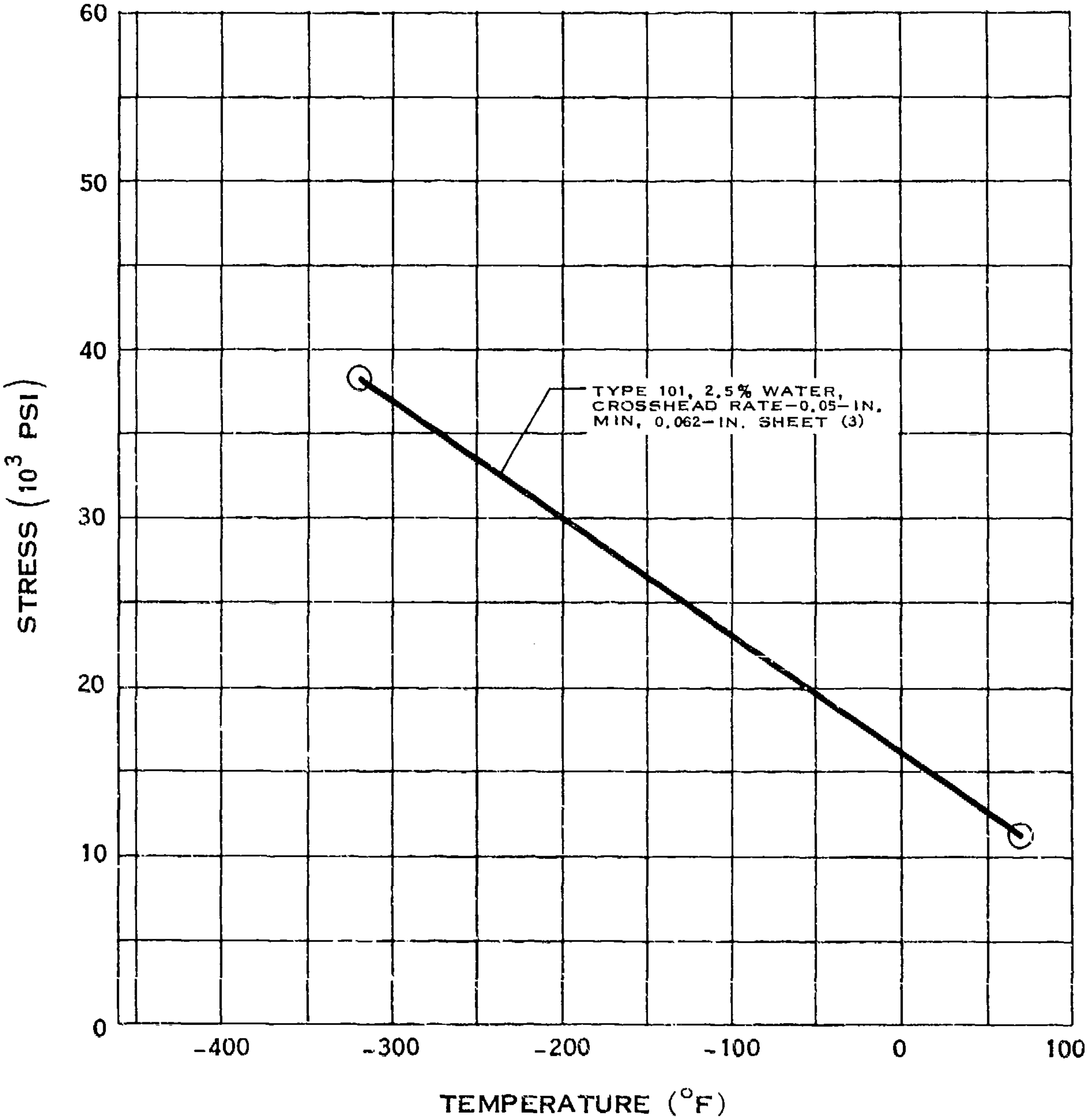
IMPACT STRENGTH OF NYLON



MODULUS OF RIGIDITY OF NYLON



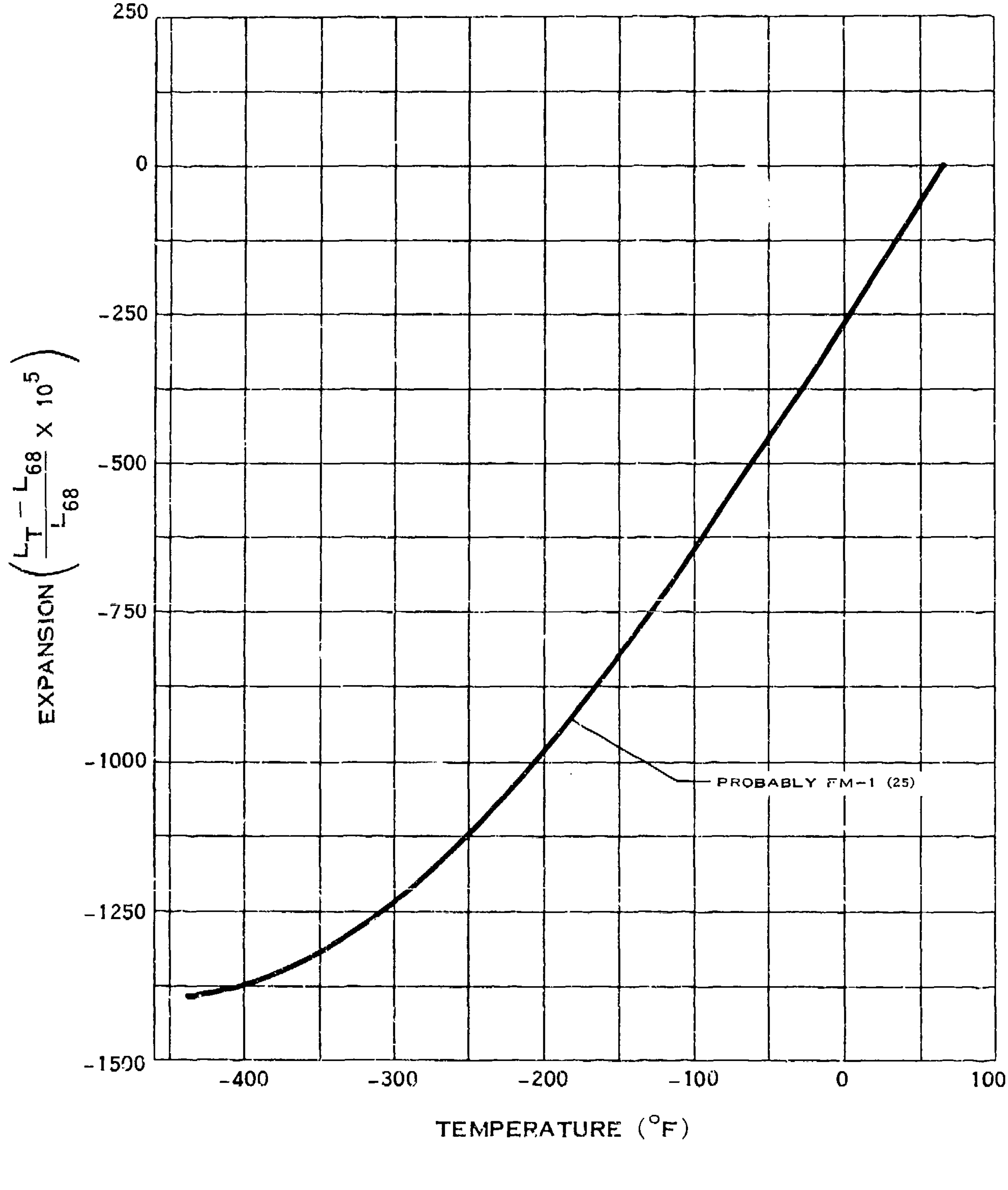
COMPRESSIVE STRENGTH OF NYLON



FLEXURAL STRENGTH OF NYLON

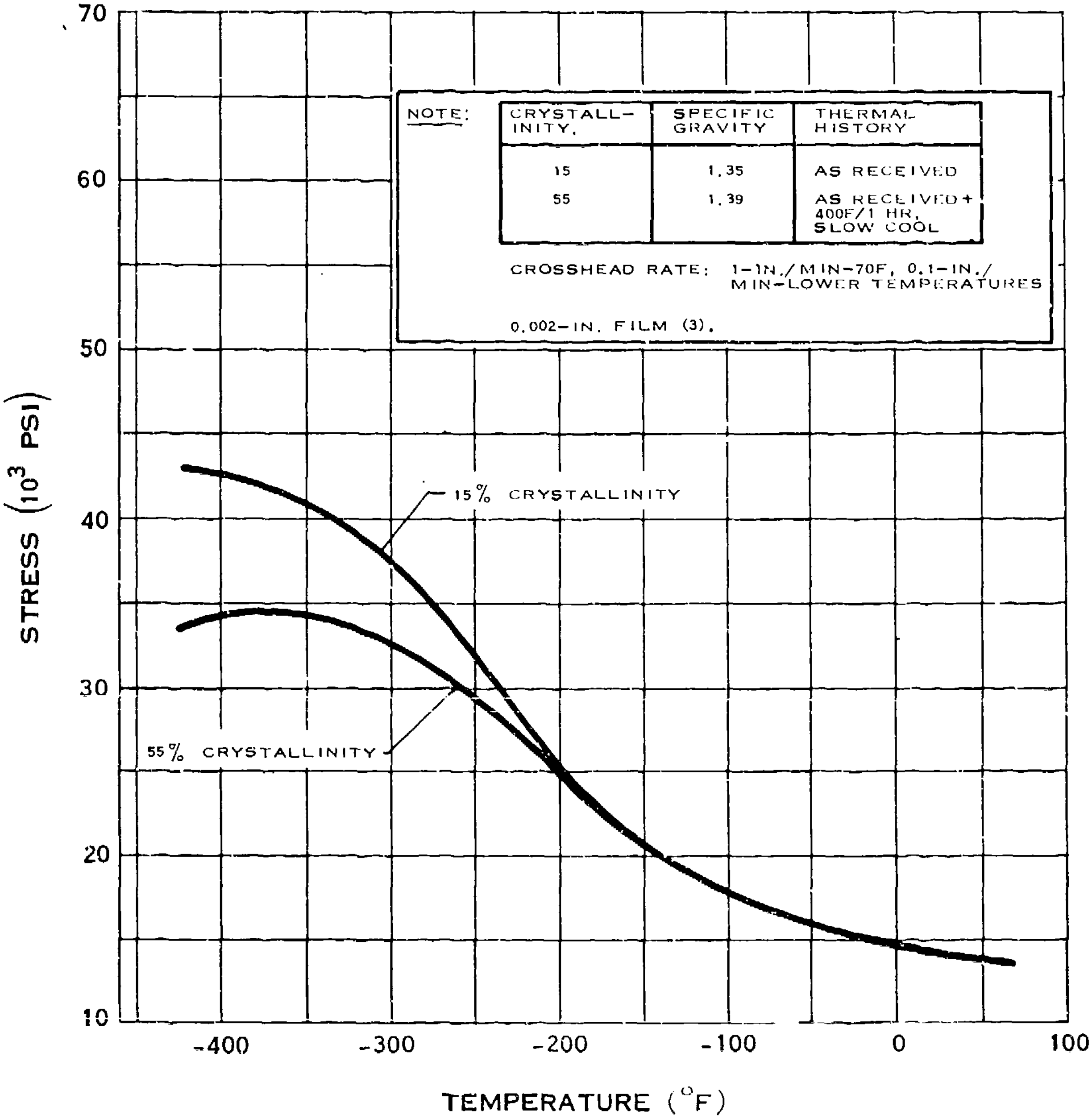
(7–64)

G.1.t



THERMAL EXPANSION OF NYLON

G.2.a

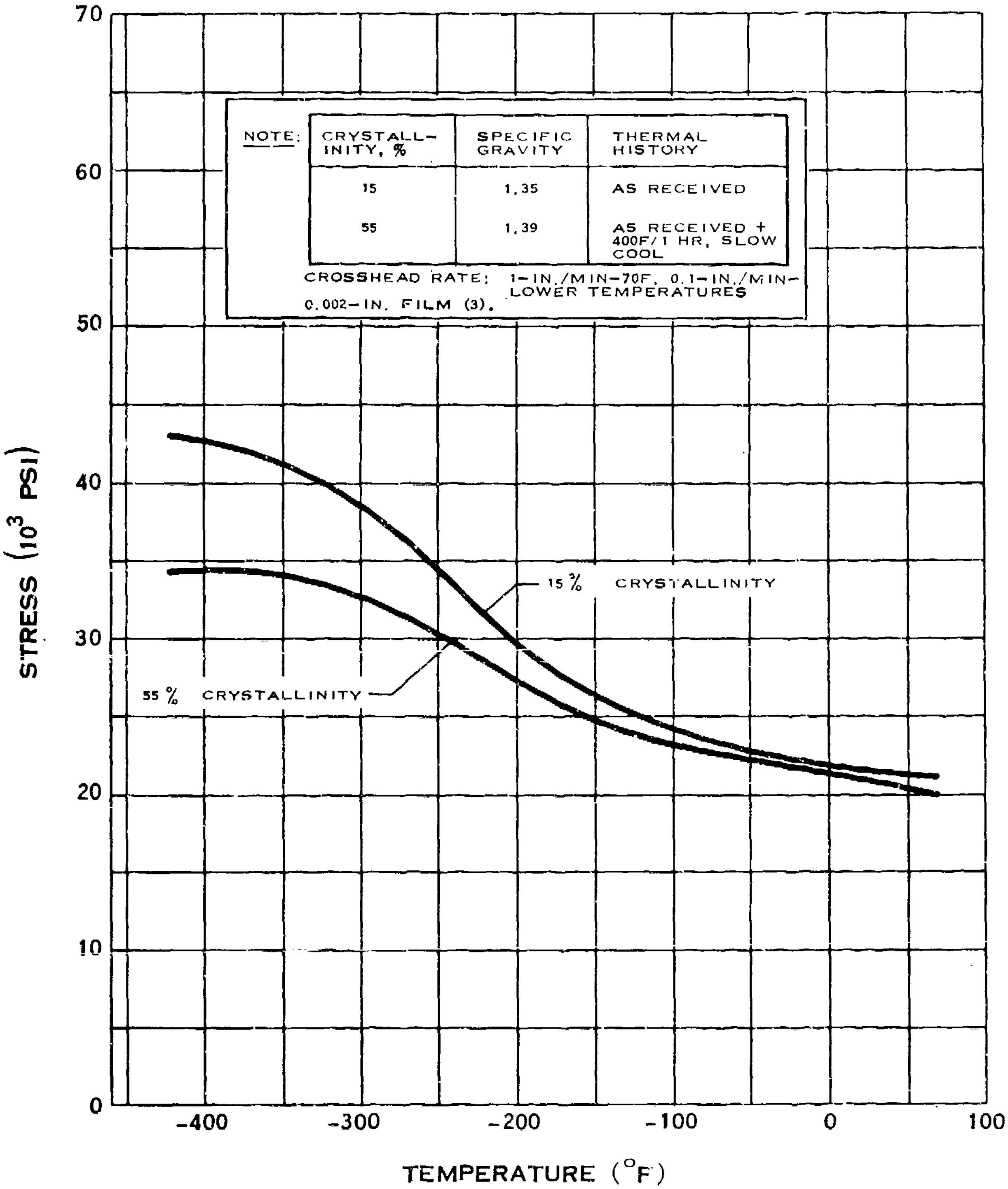


YIELD STRENGTH OF MYLAR*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

(1-65)

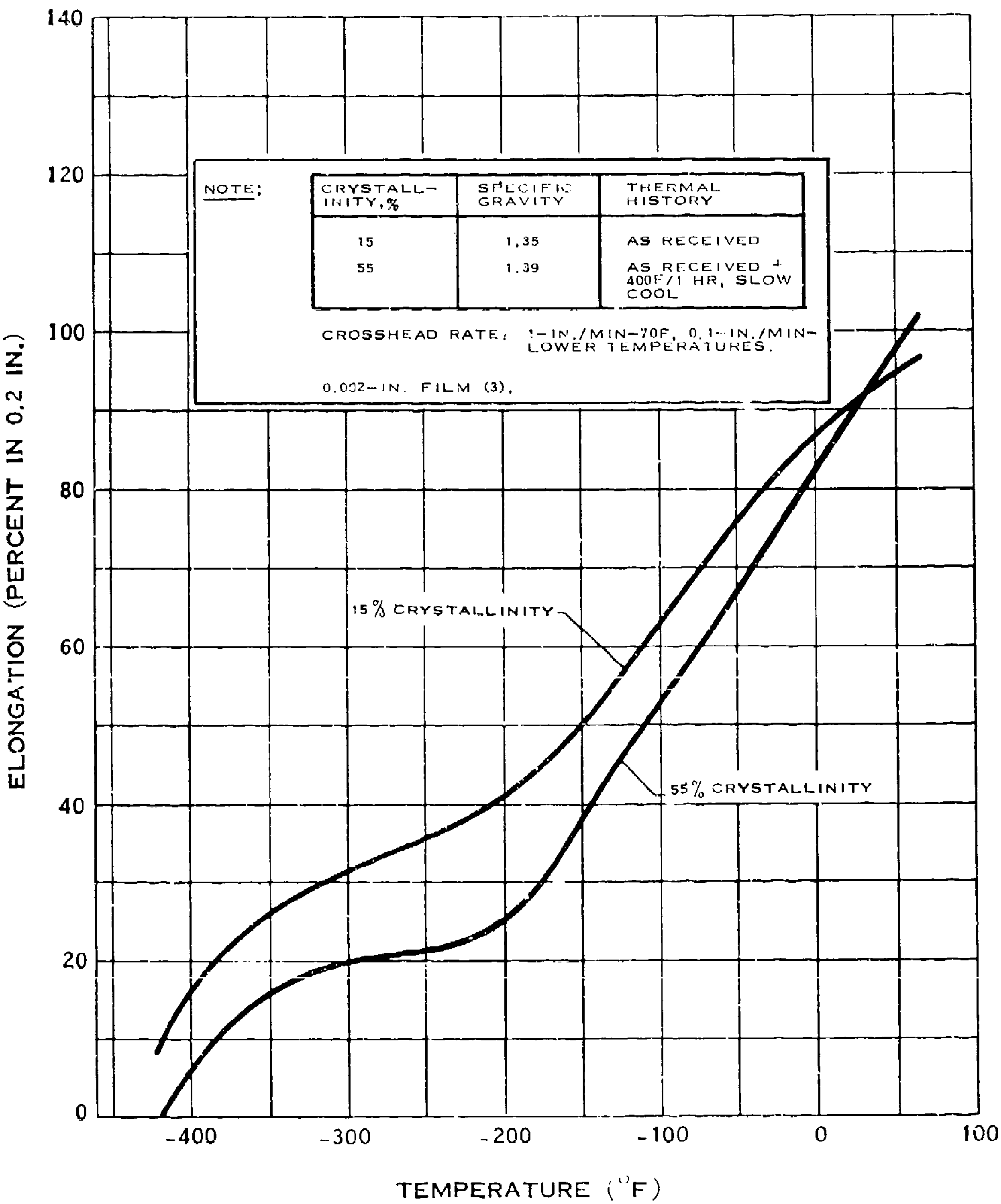
G.2.b



TENSILE STRENGTH OF MYLAR*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

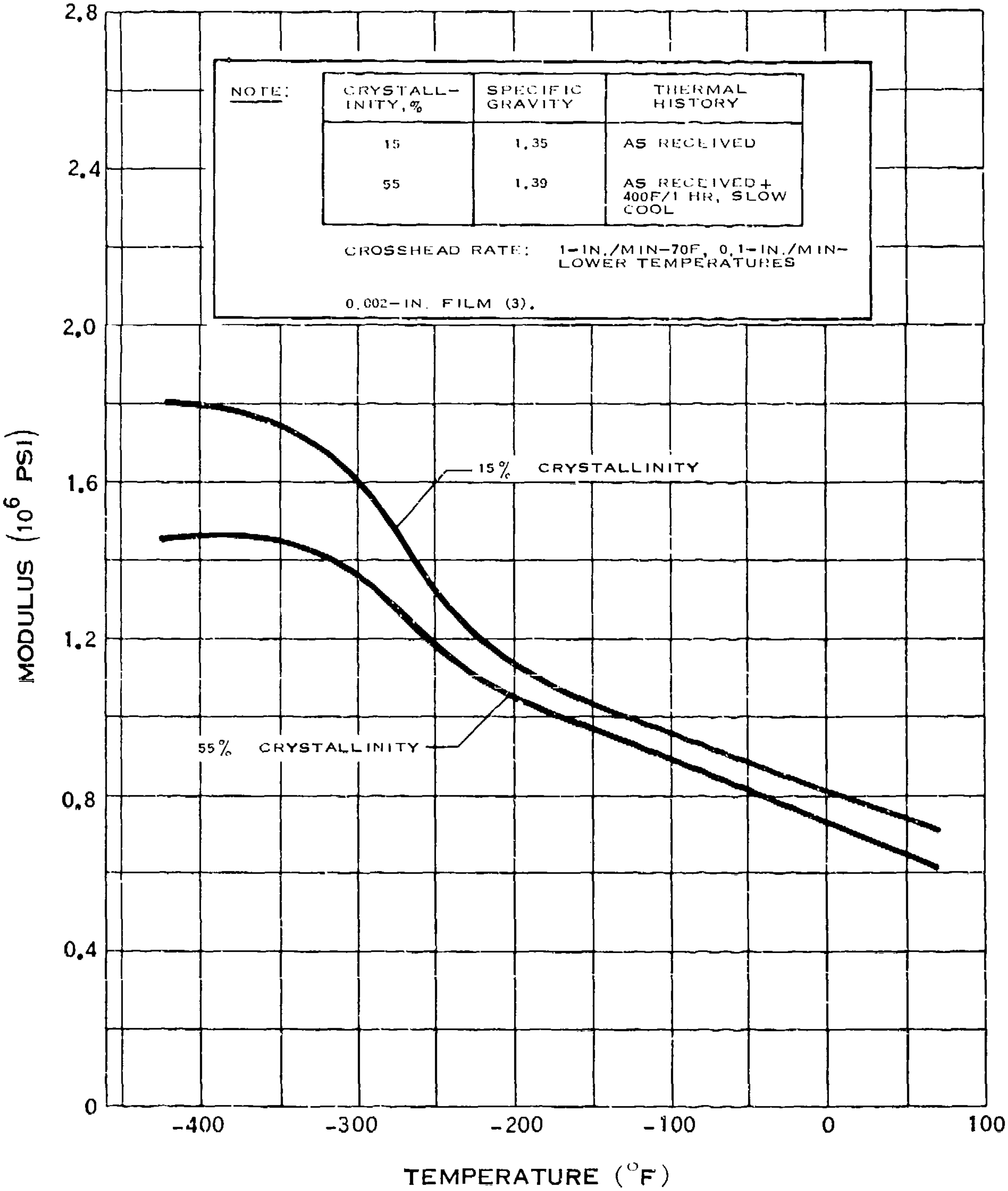
(1-65)



ELONGATION OF MYLAR*

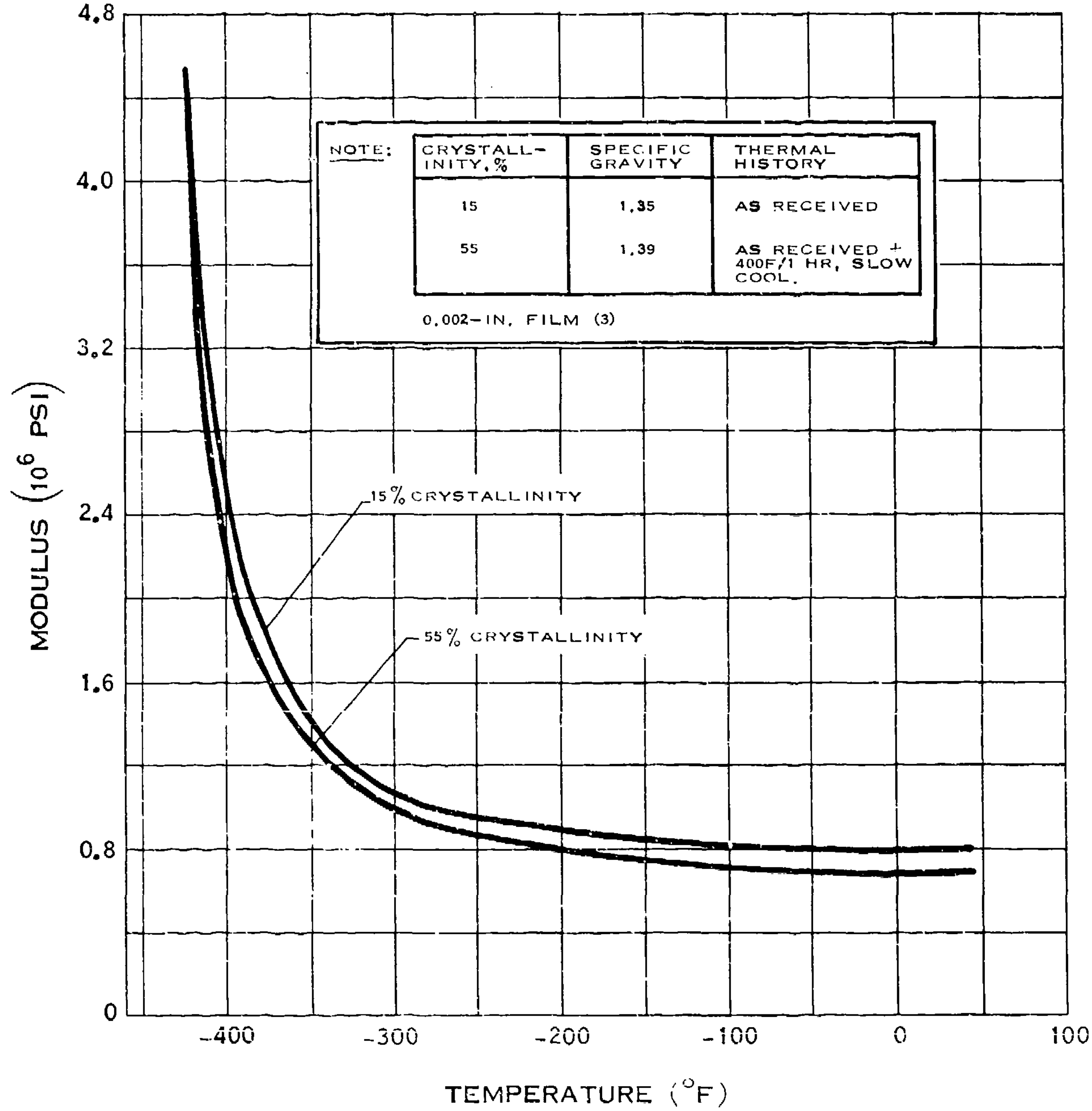
* T.M.
E. I. DUPONT DE NEMOURS AND CO.

(1-65)



MODULUS OF ELASTICITY OF MYLAR*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

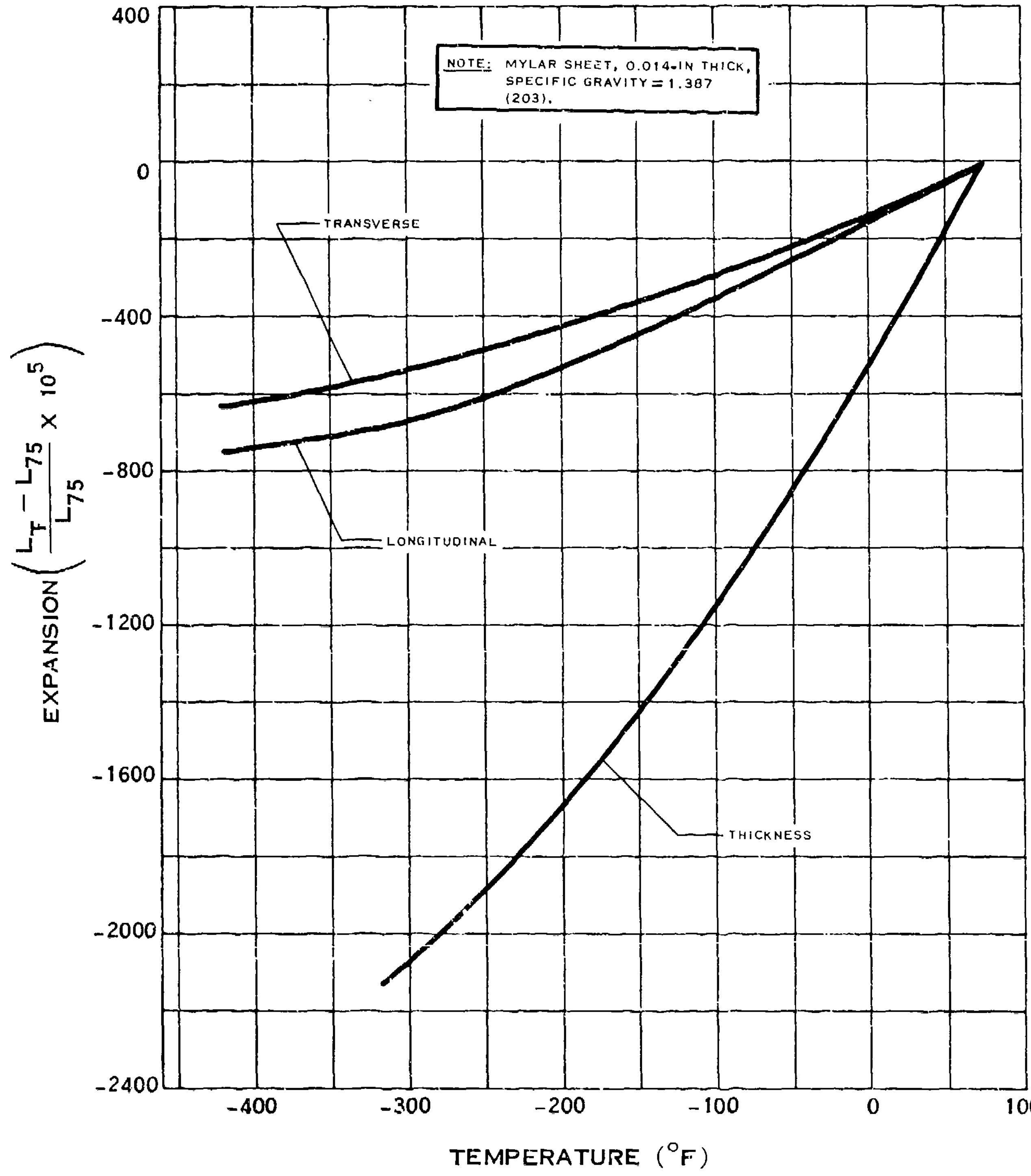


MODULUS OF RIGIDITY OF MYLAR*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

(1-65)

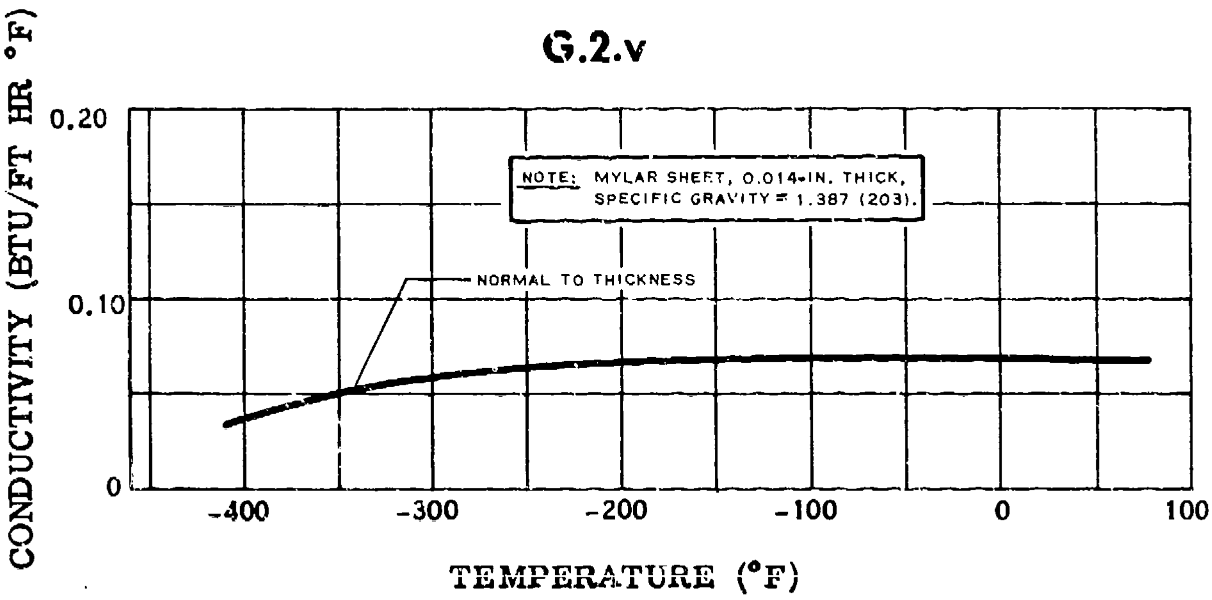
G.2.t



THERMAL EXPANSION OF MYLAR

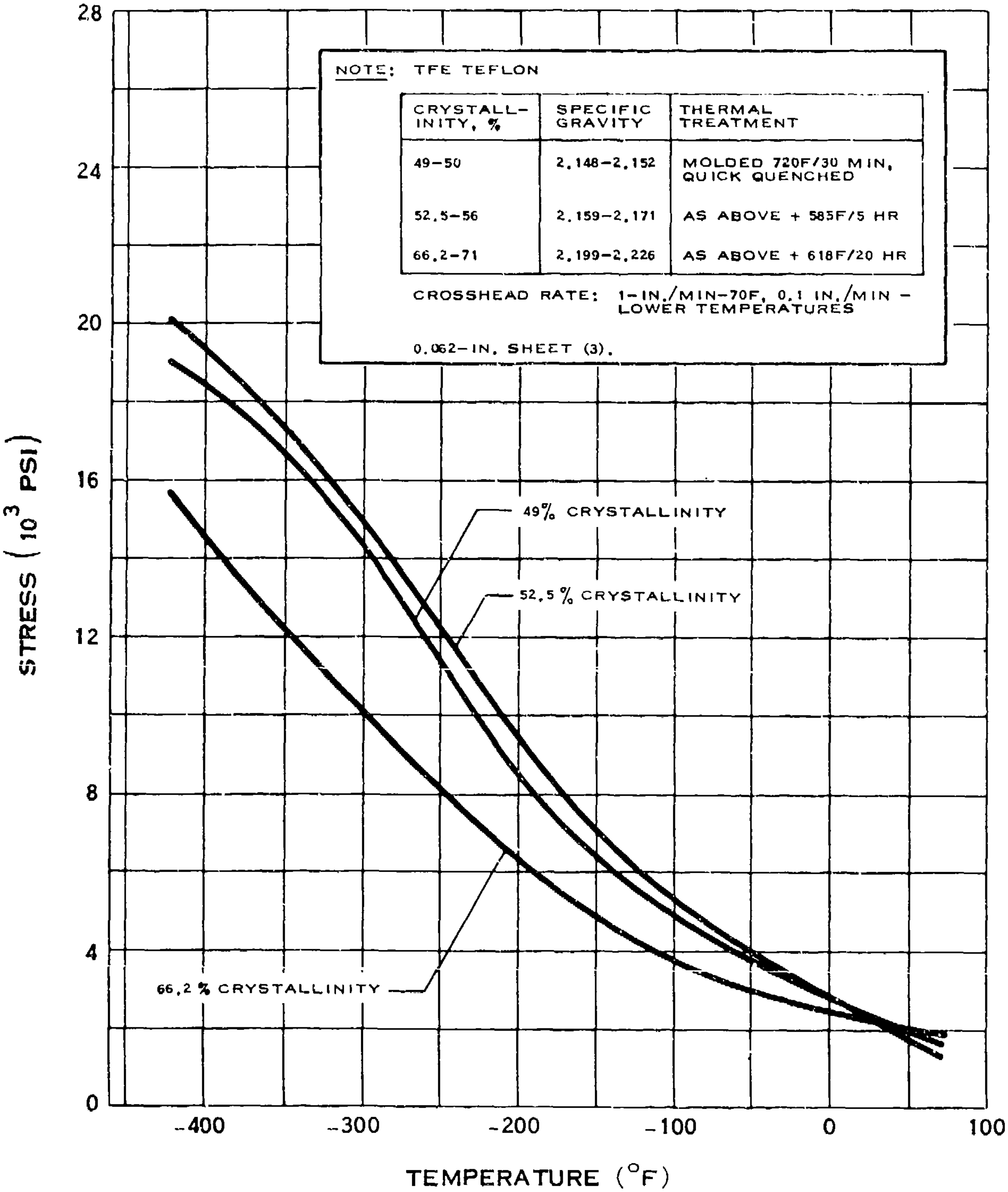
(5-68)

G.2.v



THERMAL CONDUCTIVITY OF MYLAR

(6-68)



YIELD STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

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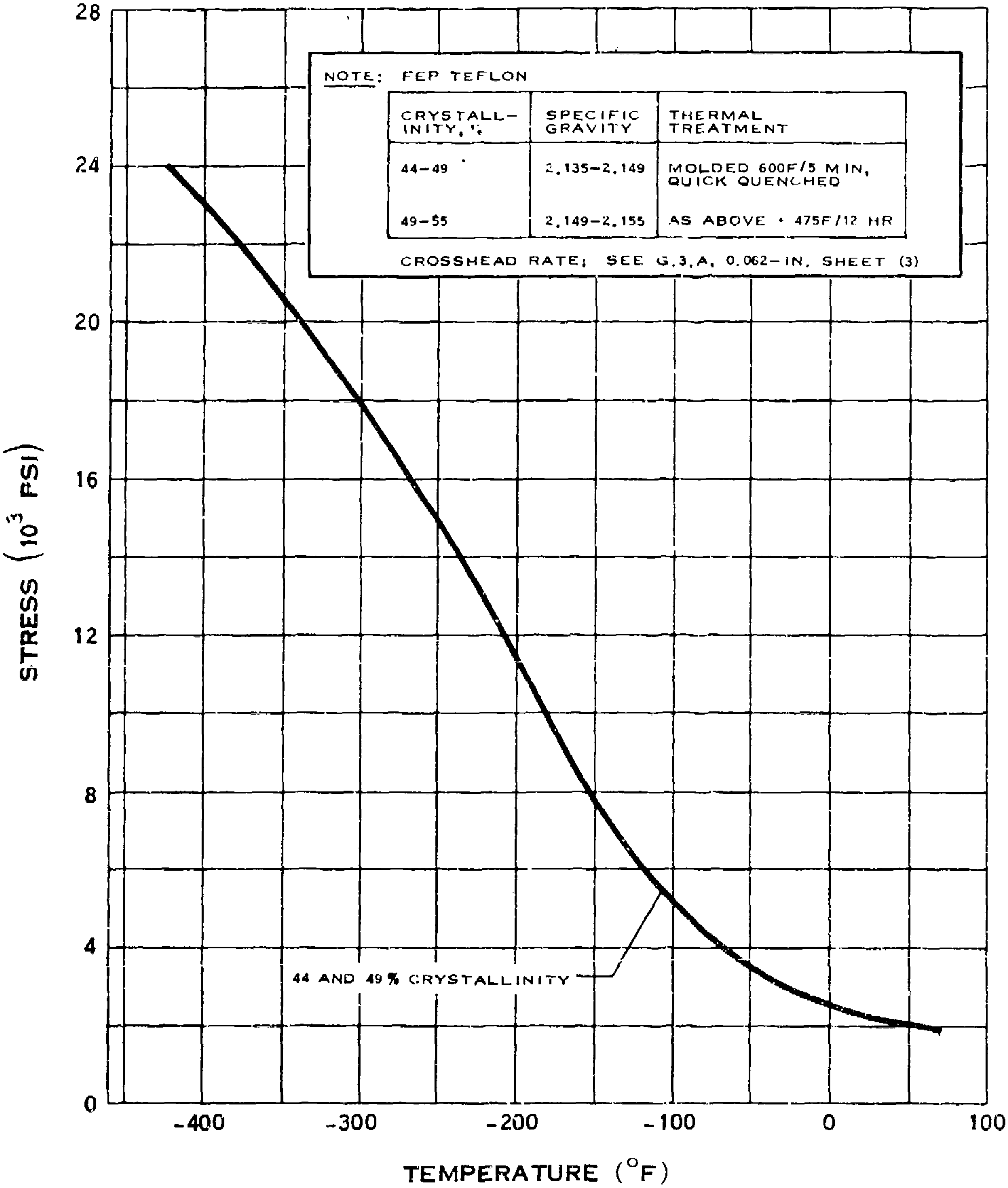
G.3.a-1

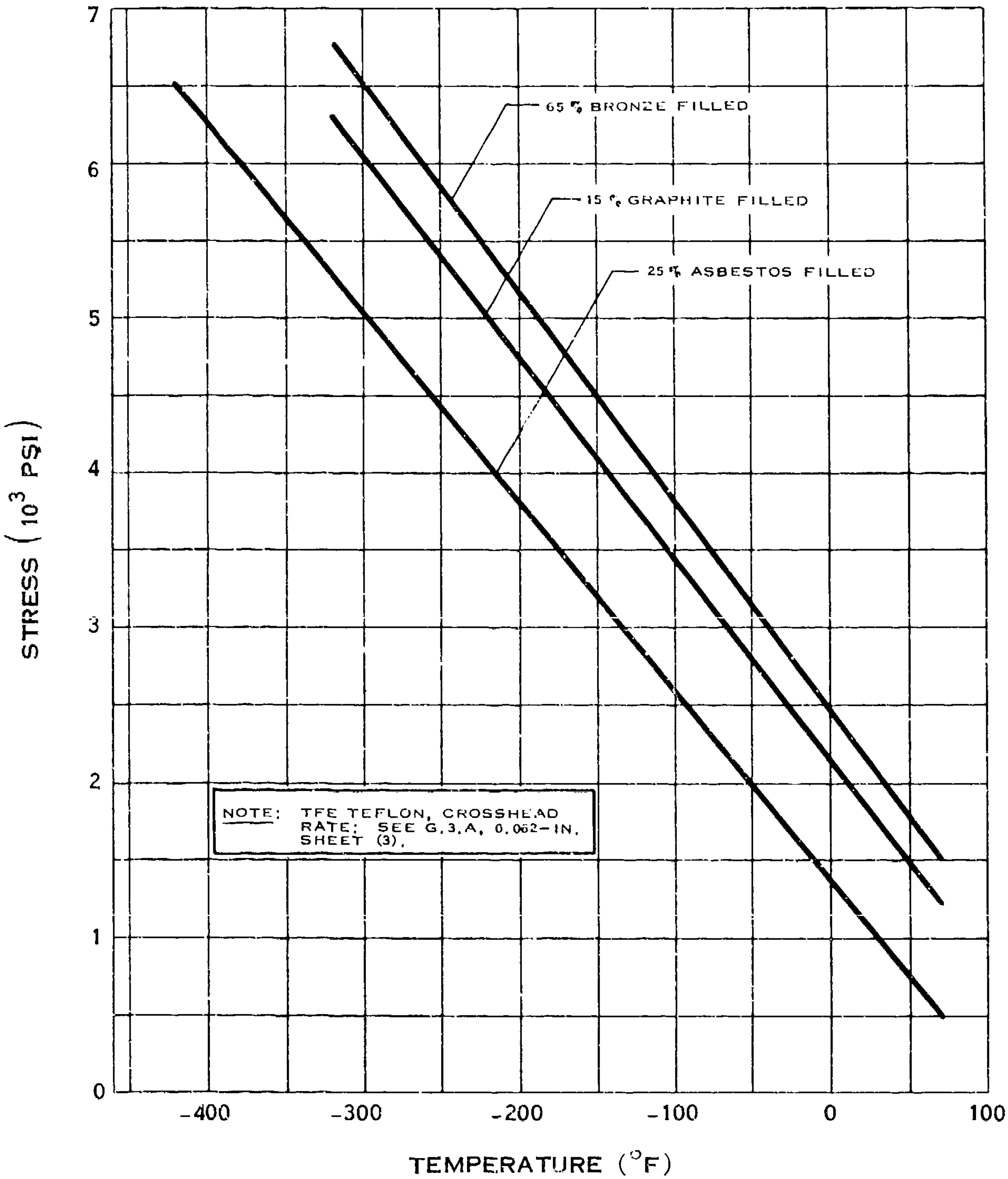


YIELD STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(1-65)

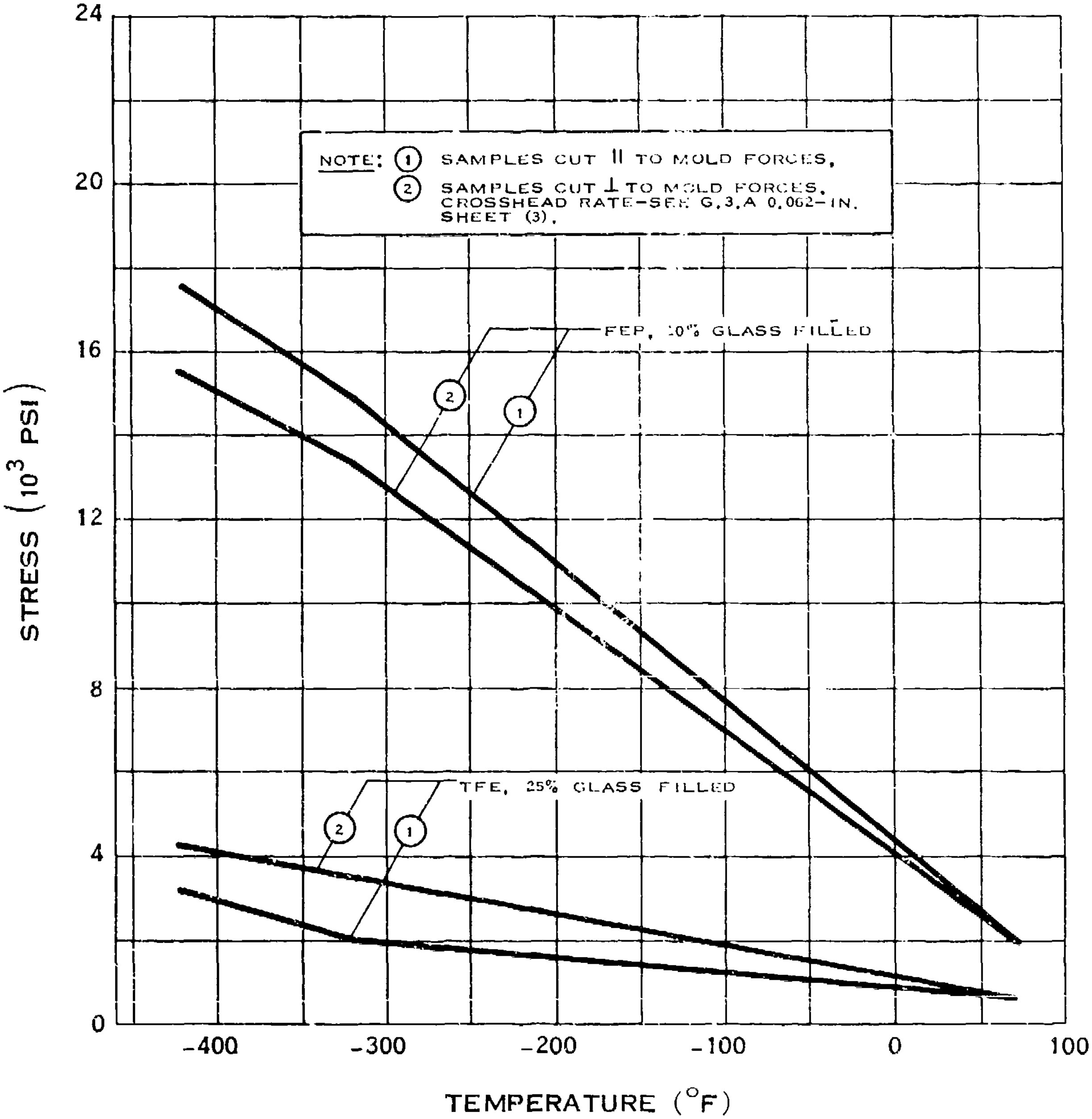
G.3.a-2



YIELD STRENGTH OF TEFLON*

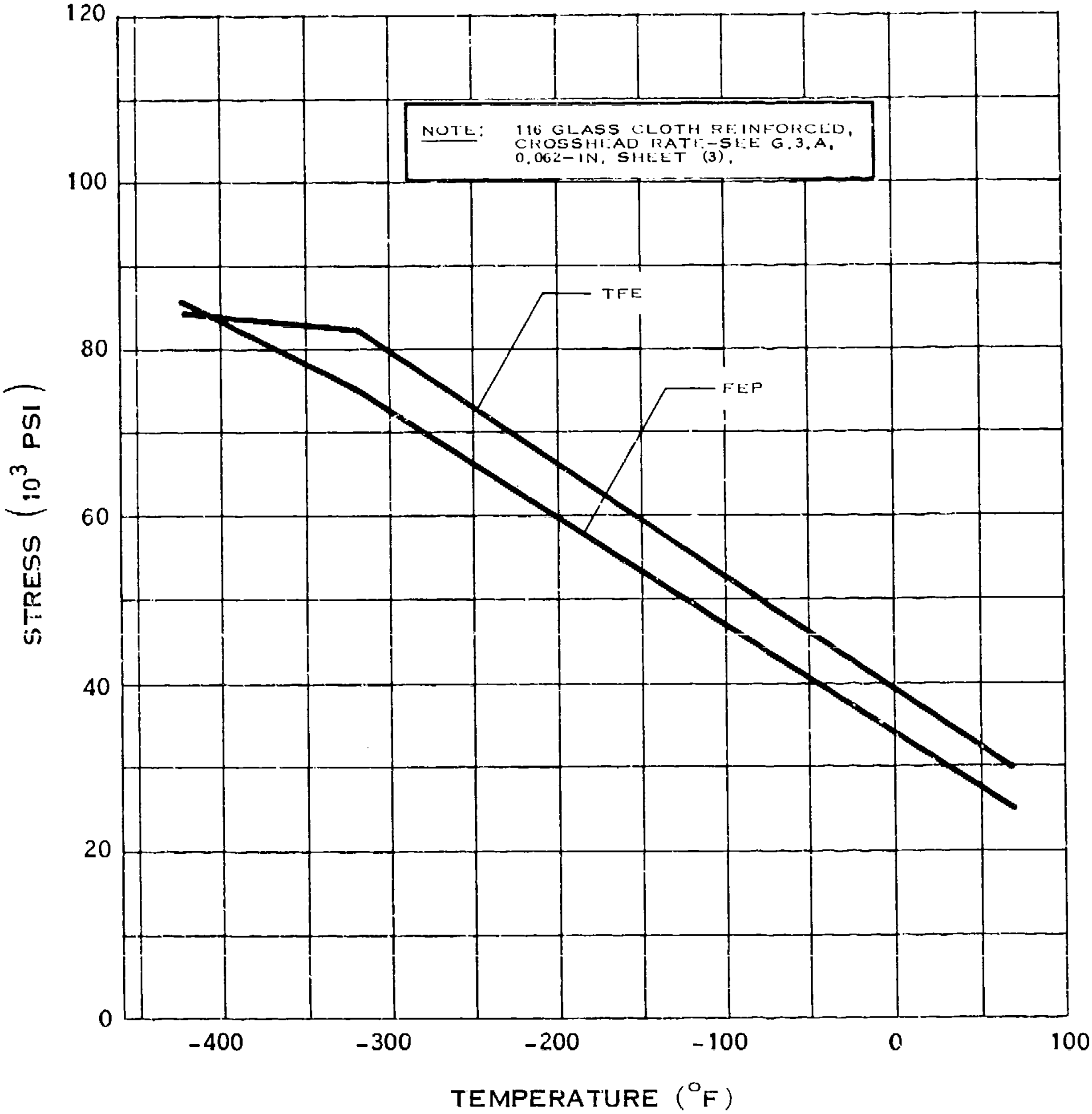
* E. I. DUPONT DE NEMOURS AND CO.

(7-64)



YIELD STRENGTH OF TEFLON*

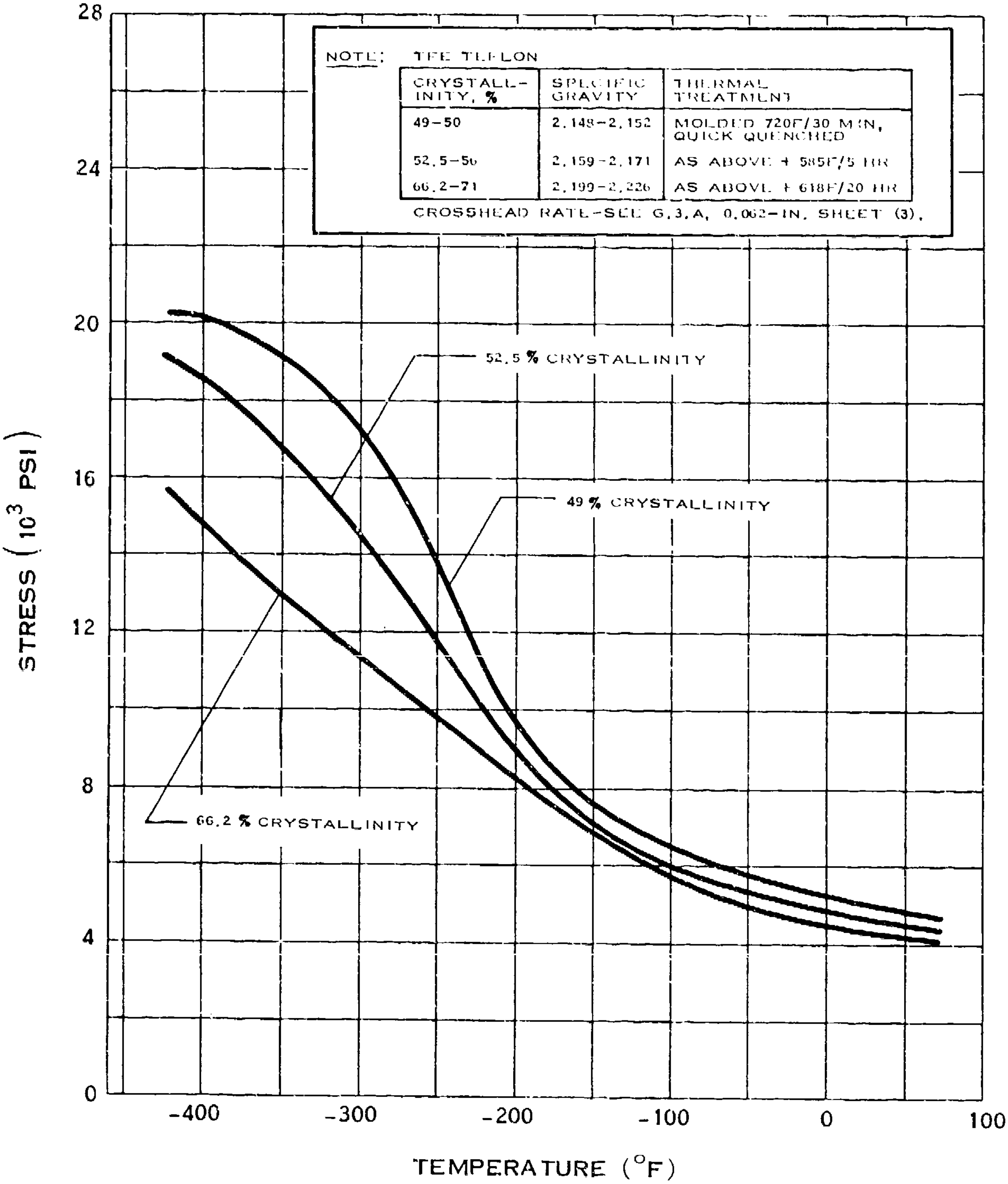
* T.M. E. I. DUPONT DE NEMOURS AND CO.



YIELD STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

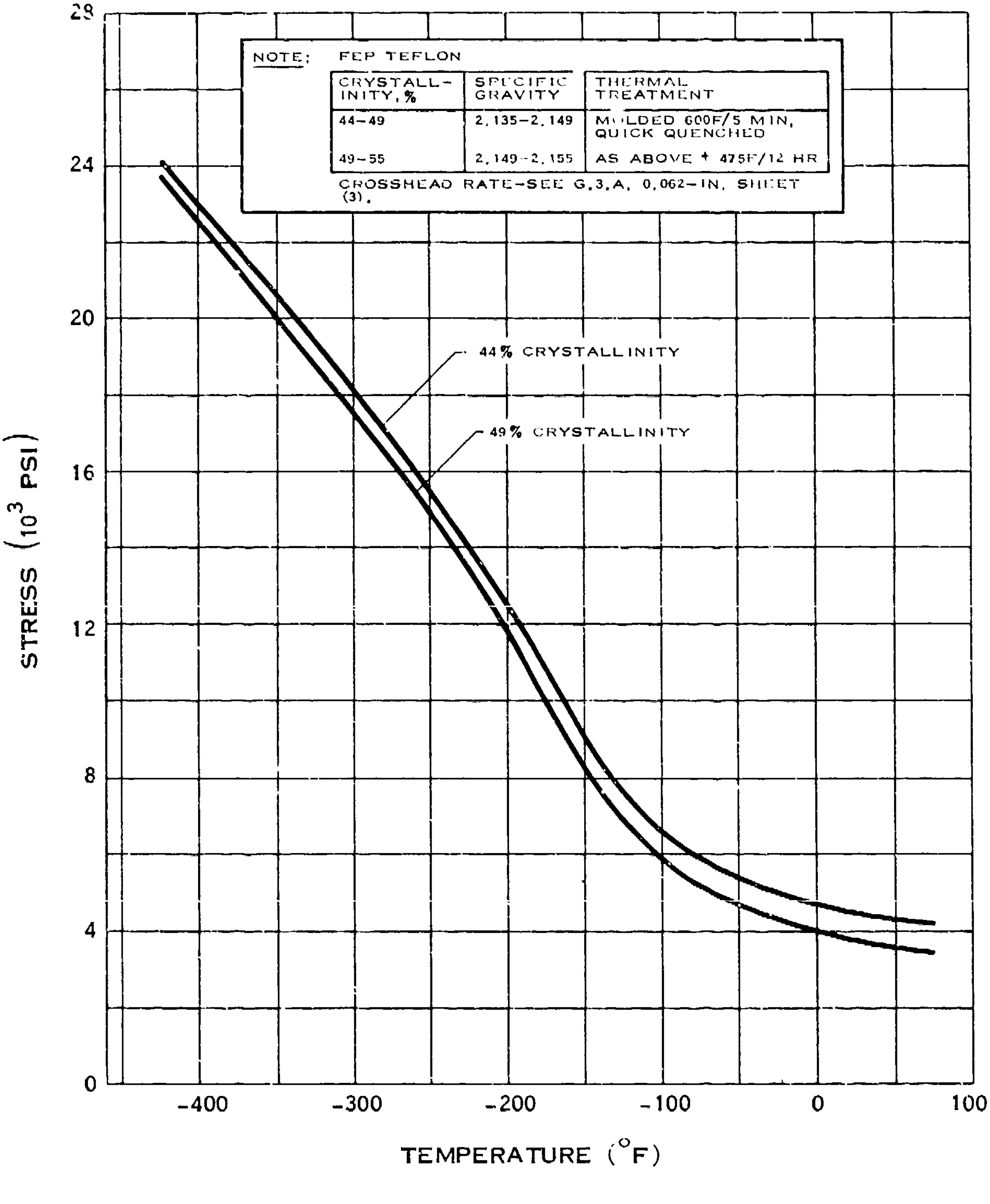
G.3.b



TENSILE STRENGTH OF TEFLON*

*T.M. E. I. DUPONT DE NEMOURS AND CO.

G.3.b-1

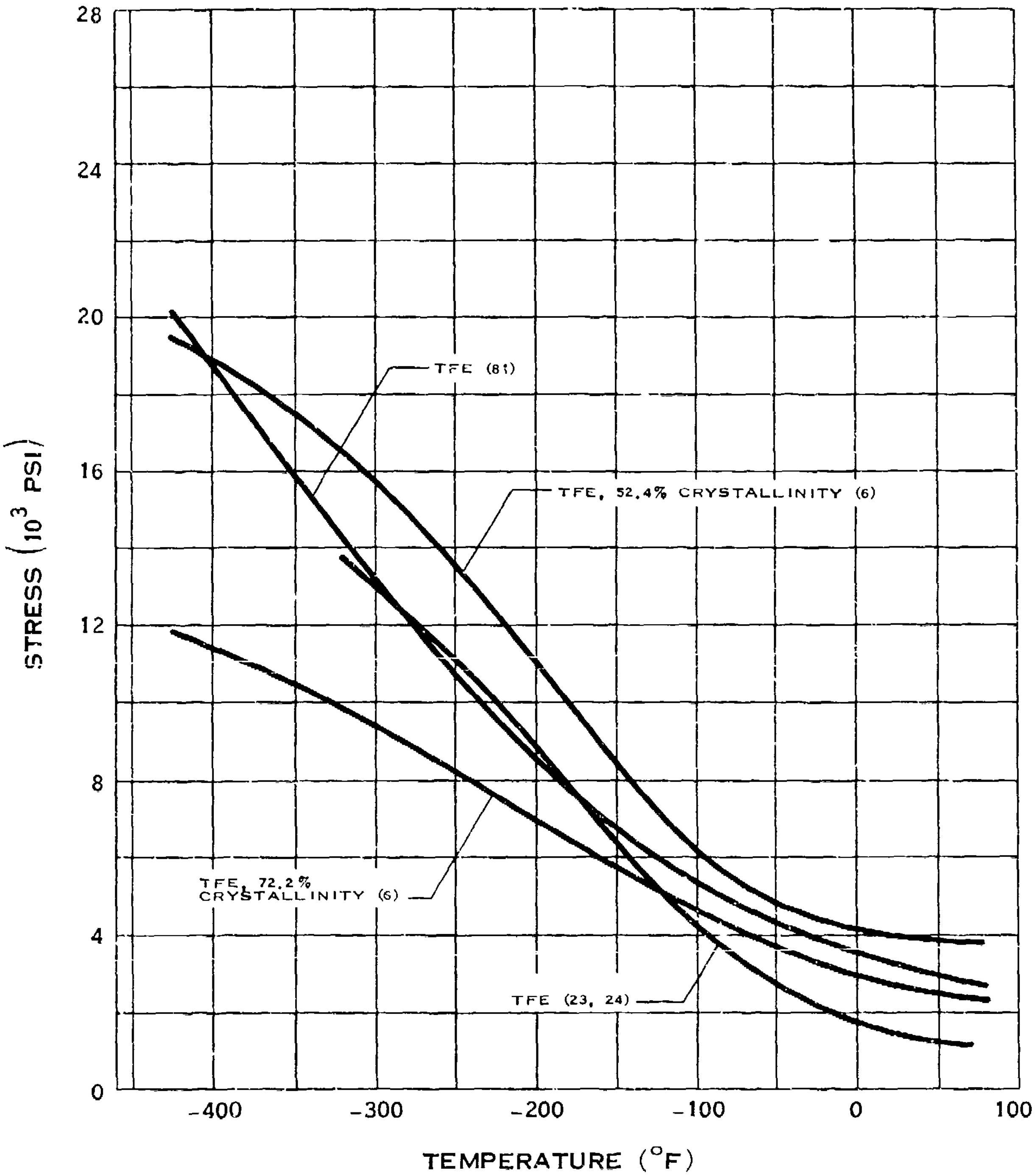


TENSILE STRENGTH OF TEFLON*

*T.M. E. I. DUPONT DE NEMOURS AND CO.

(7–64)

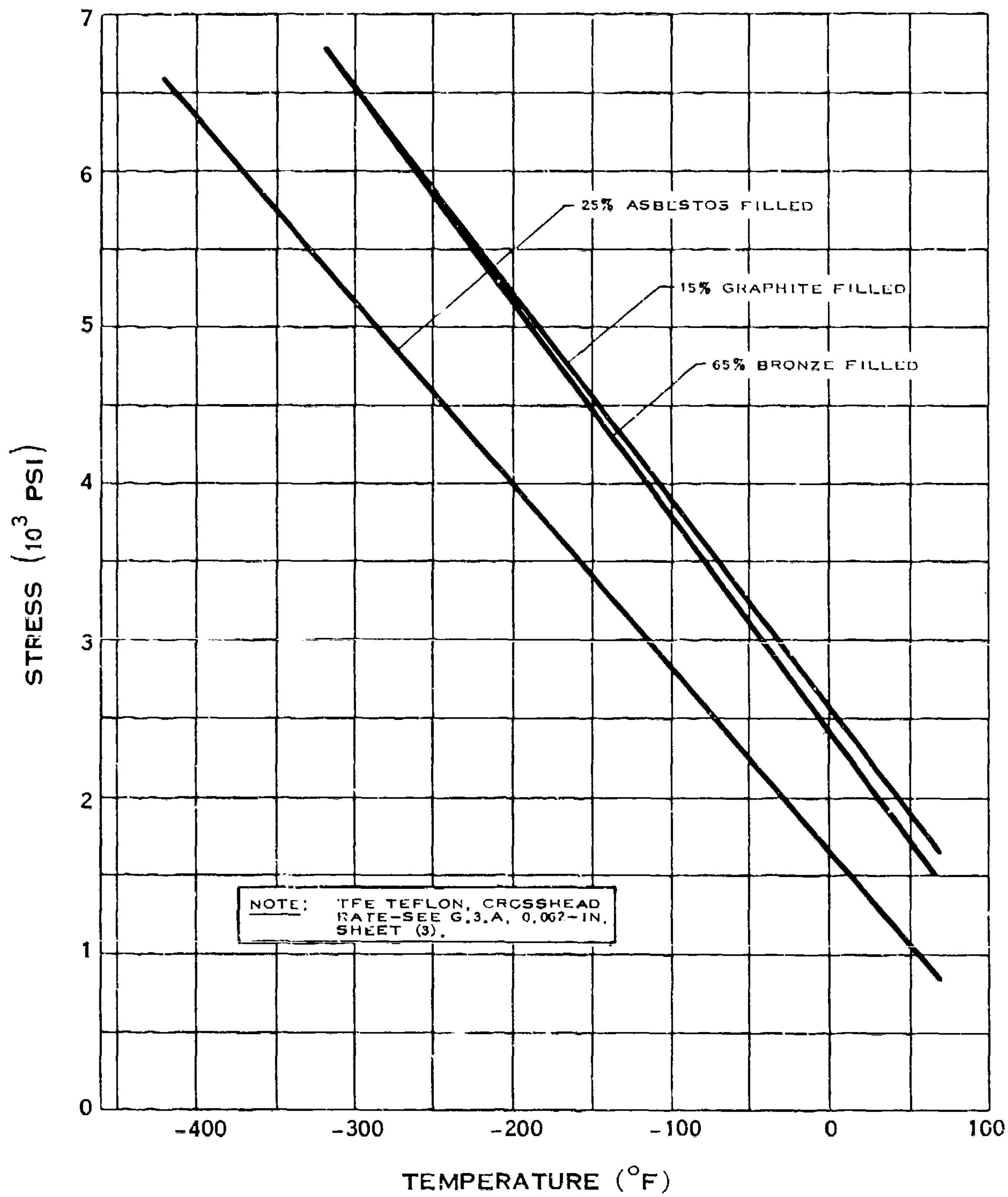
G.3.b-2



TENSILE STRENGTH OF TEFLON*

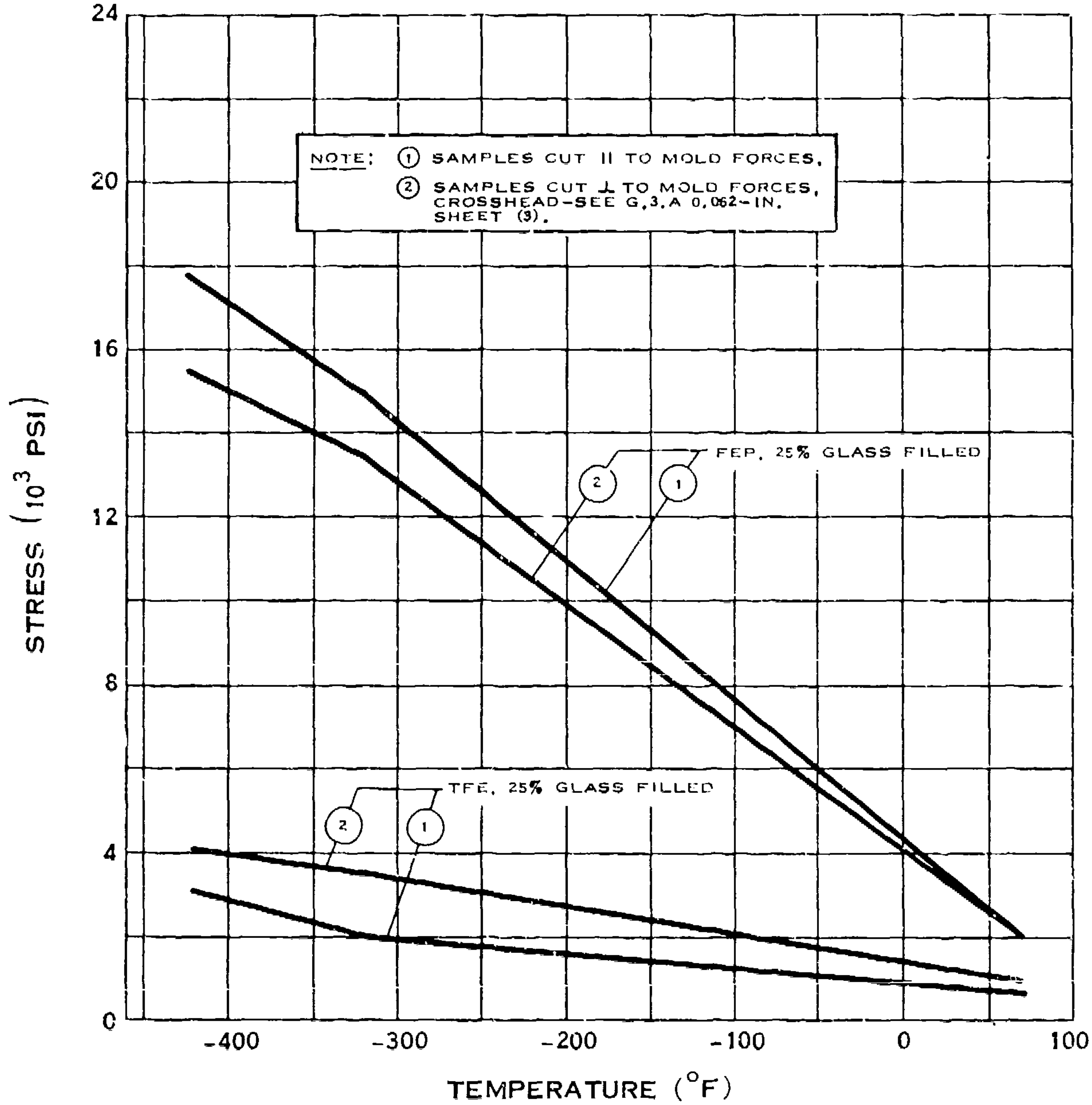
* T.M.
E. I. DUPONT DE NEMOURS AND CO.

G.3.b-3



TENSILE STRENGTH OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

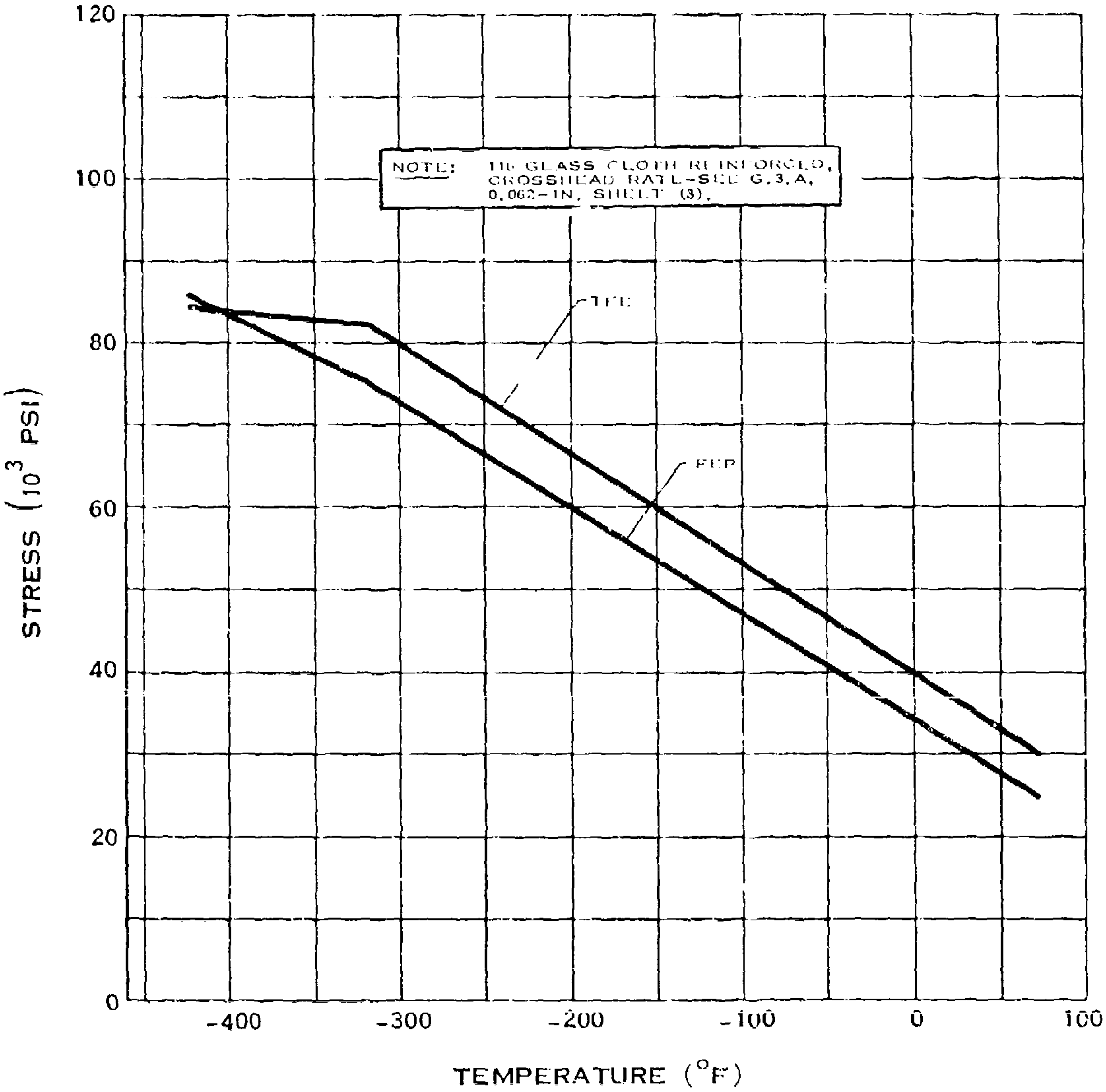


TENSILE STRENGTH OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

(7-64)

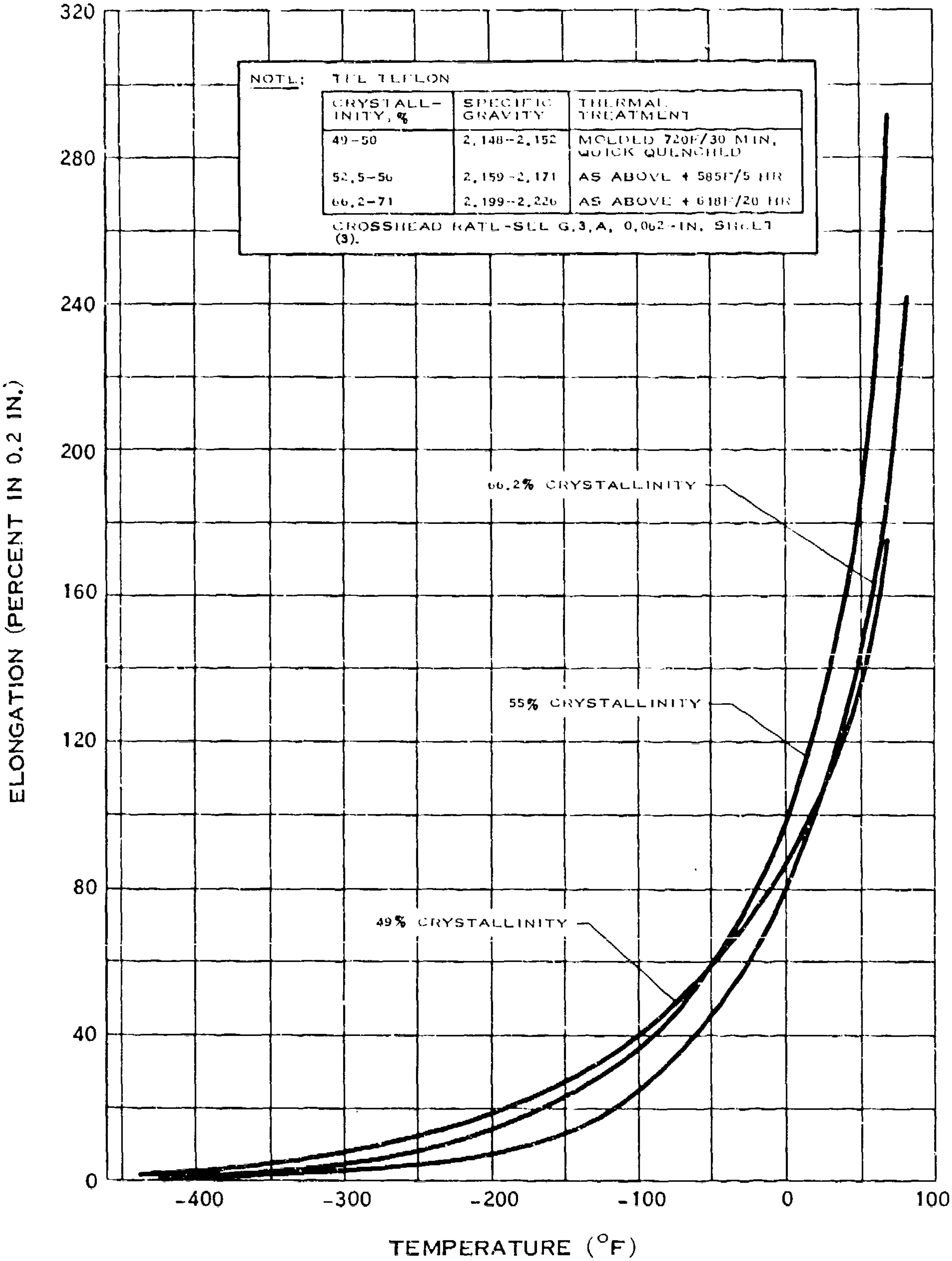
G.3.b-5



TENSILE STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

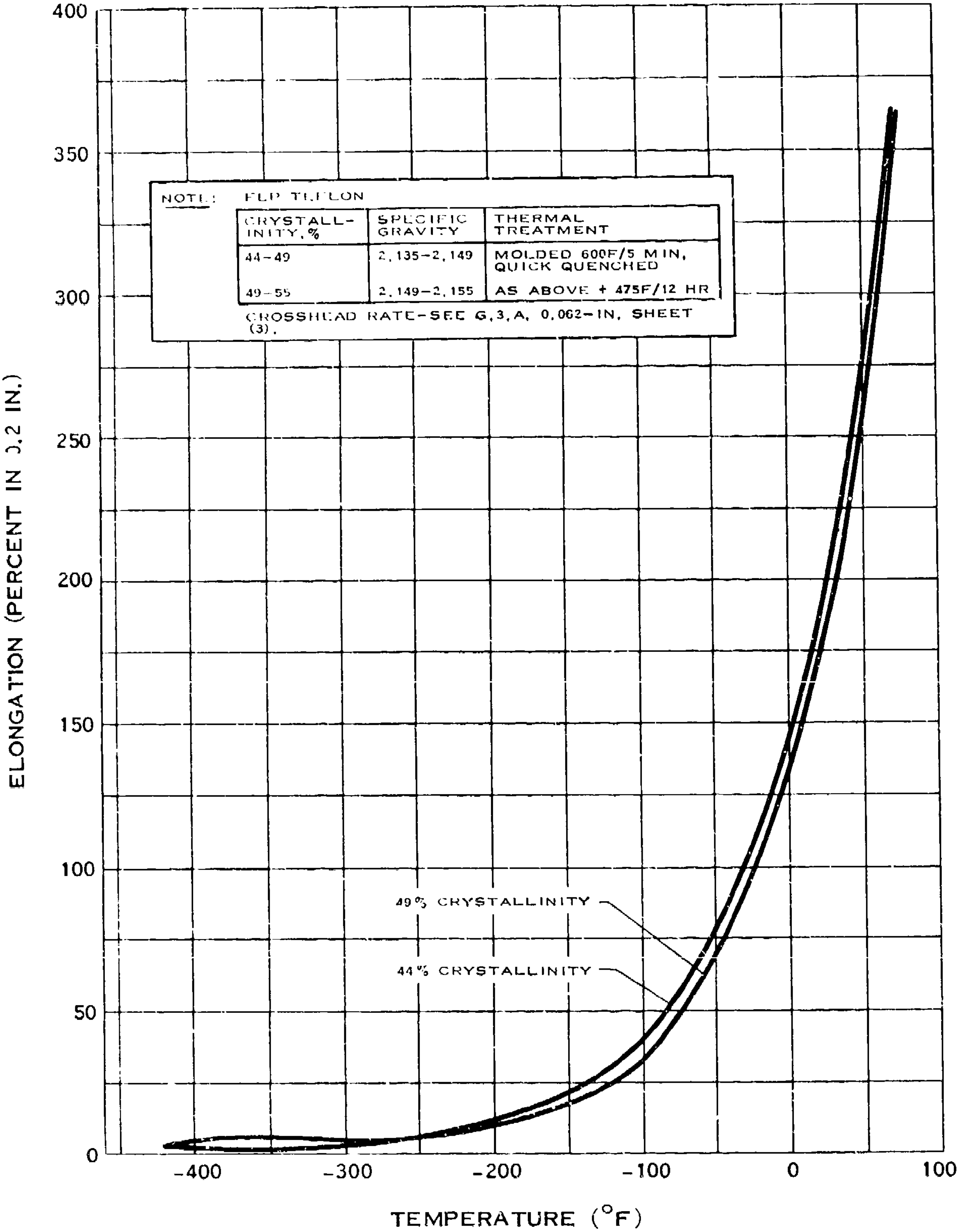
(7-64)



ELONGATION OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

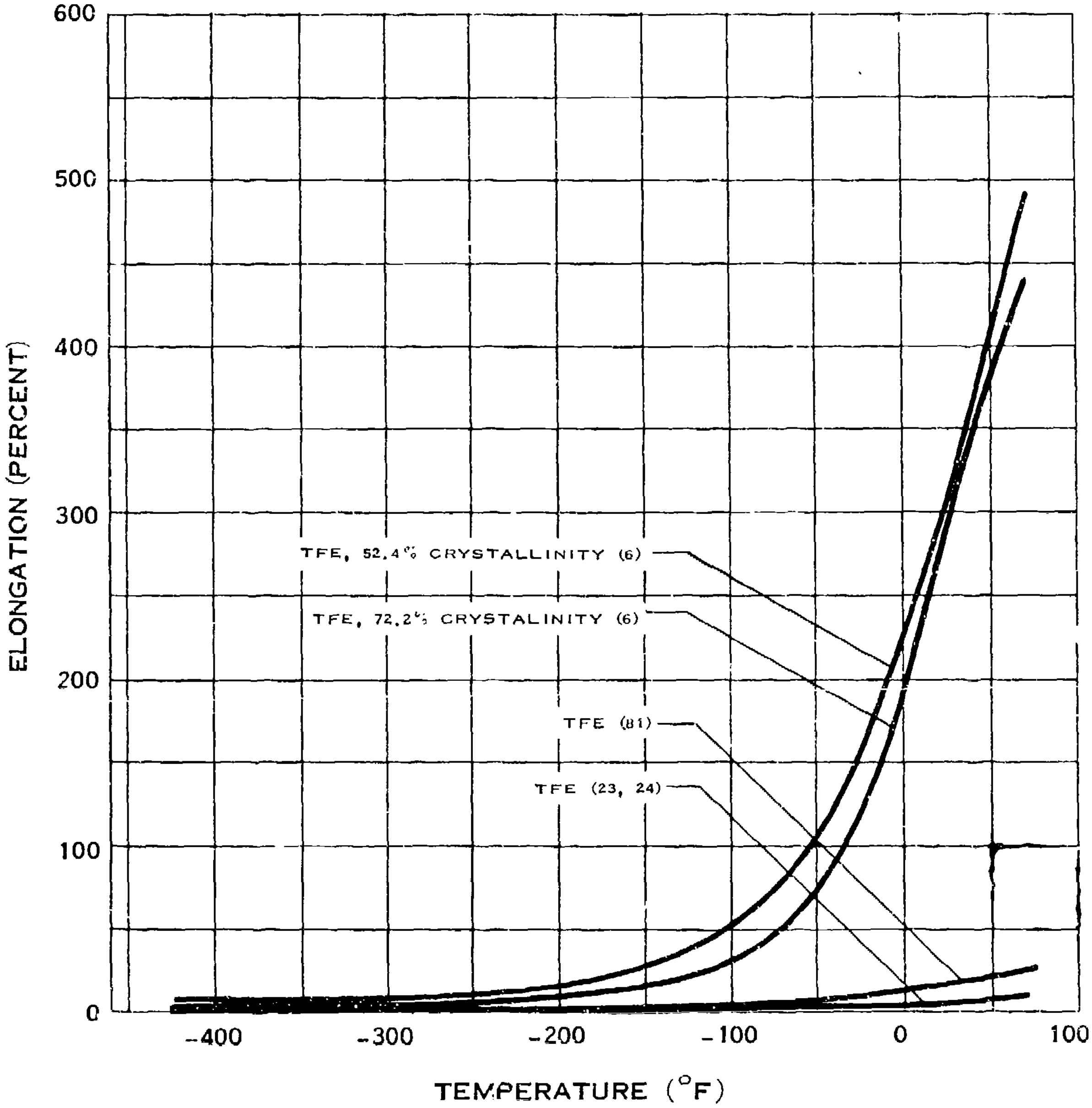
(7-64)



ELONGATION OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

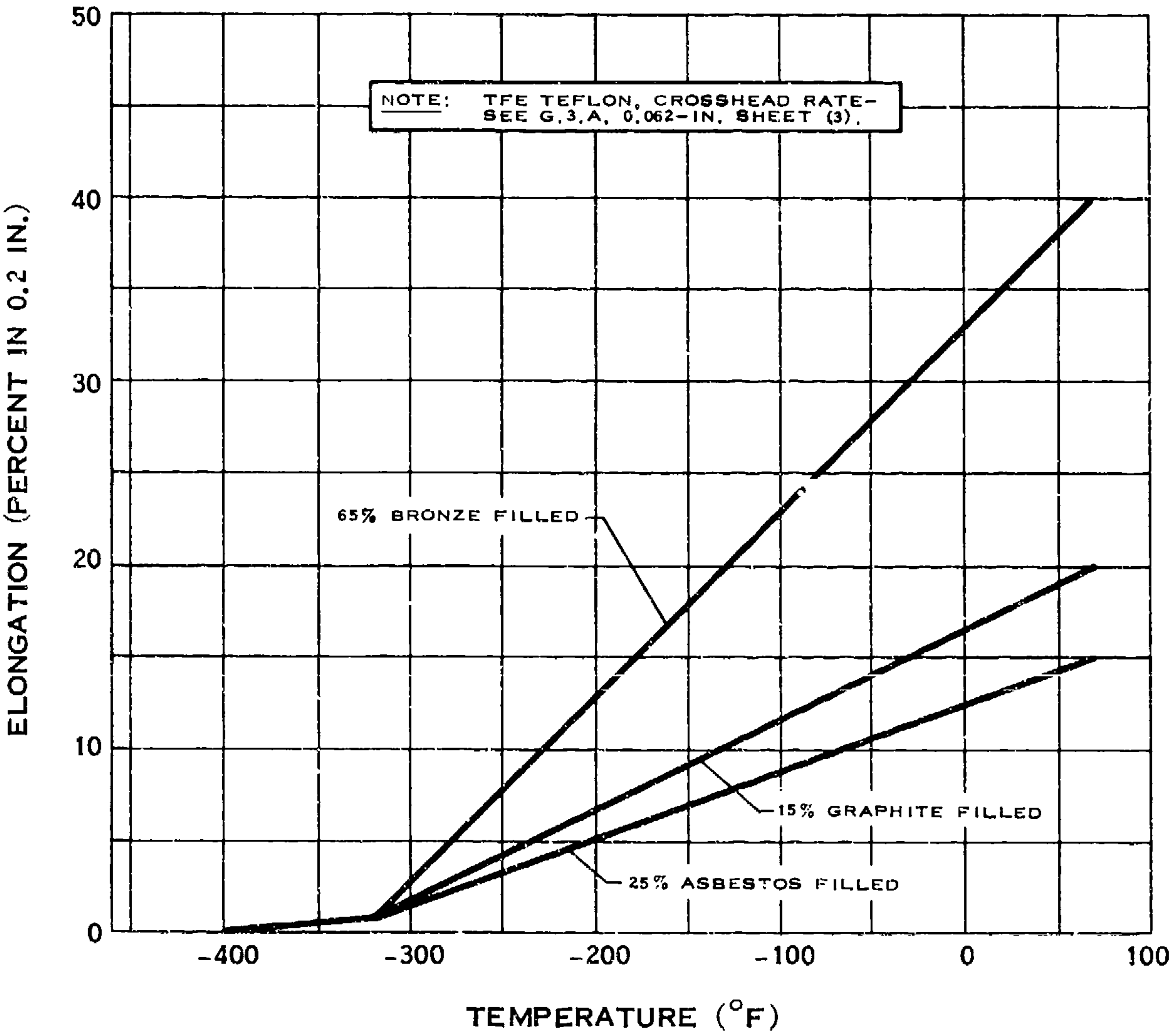
(7-64)



ELONGATION OF TEFLON*

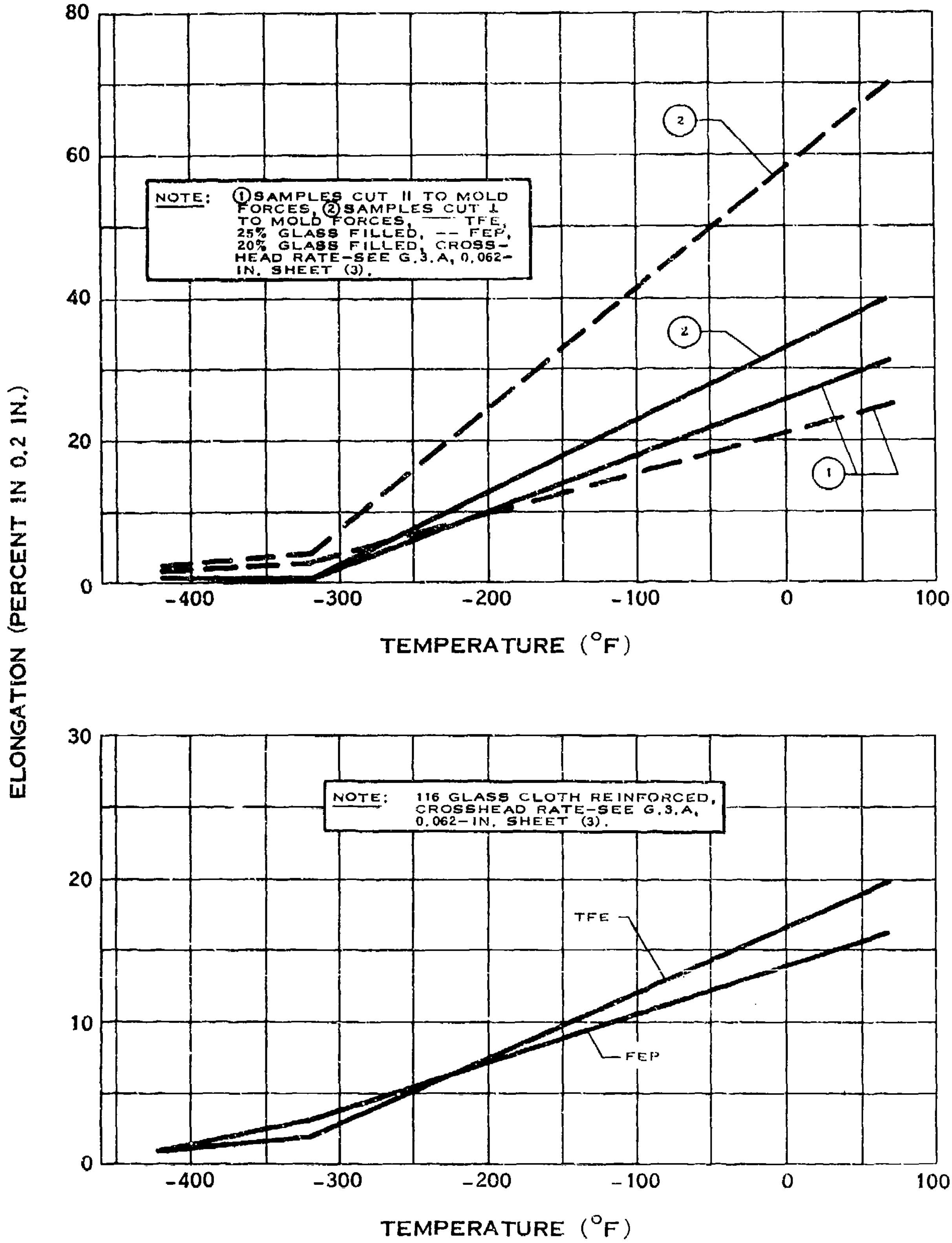
*T.M. E. I. DUPONT DE NEMOURS AND CO.

G.3.c-3



ELONGATION OF TEFLON*

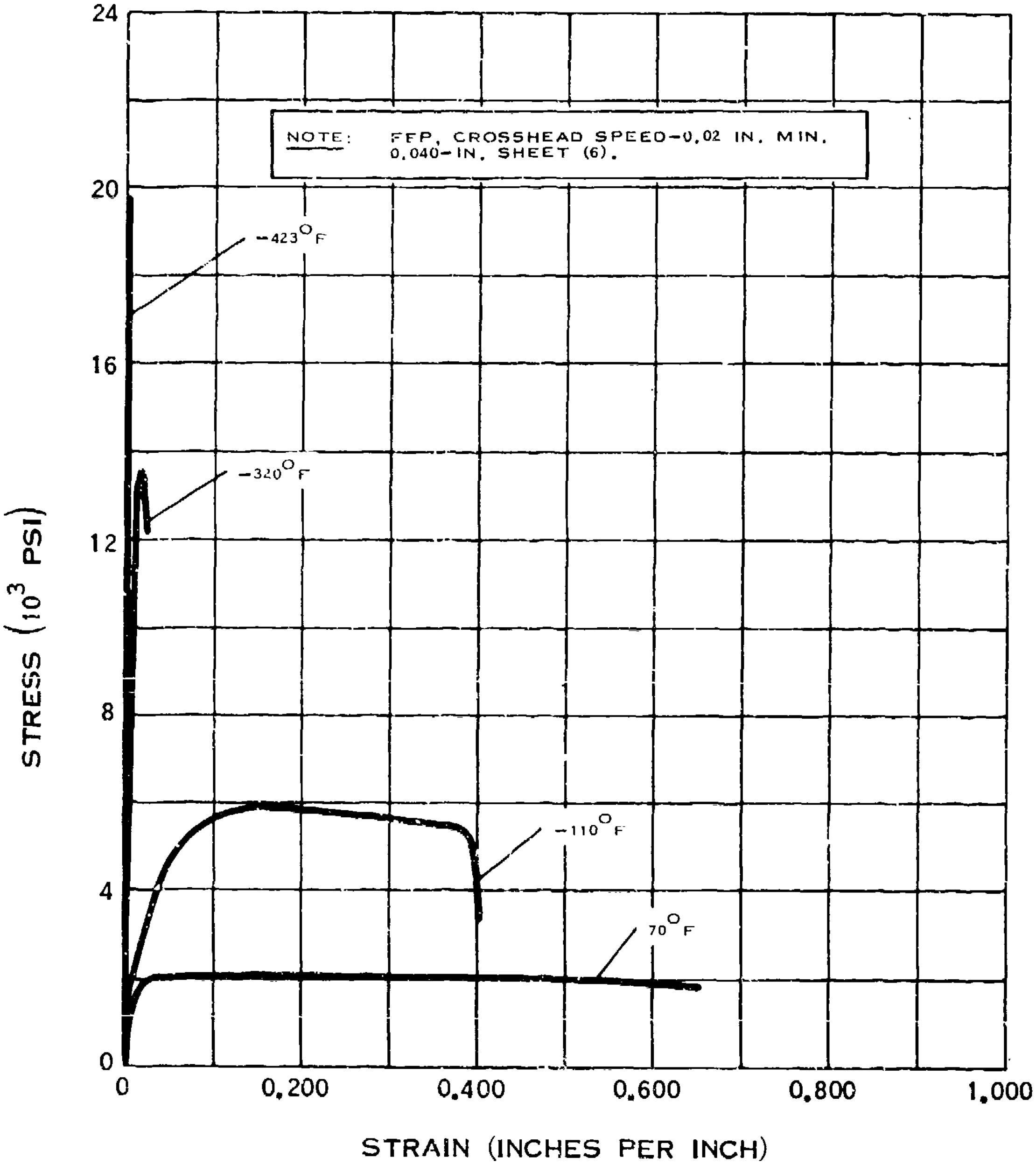
* T.M.
E. I. DUPONT DE NEMOURS AND CO.



ELONGATION OF TEFLON*

*T.M. E. I. DUPONT DE NEMOURS AND CO.

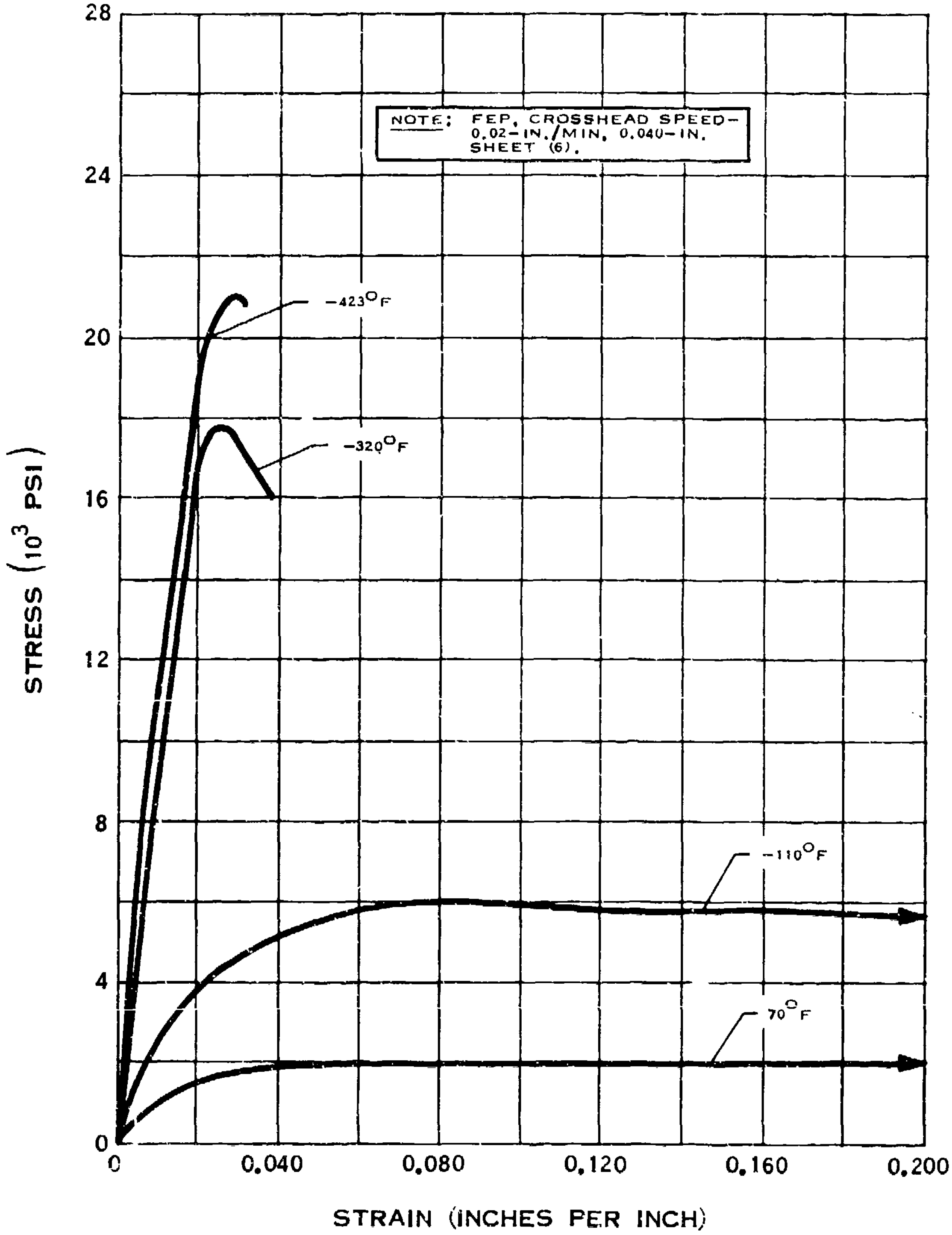
(7-64)



STRESS-STRAIN DIAGRAM FOR TEFLON*

*T.M.
E. I. DUPONT DE NEMOURS AND CO.

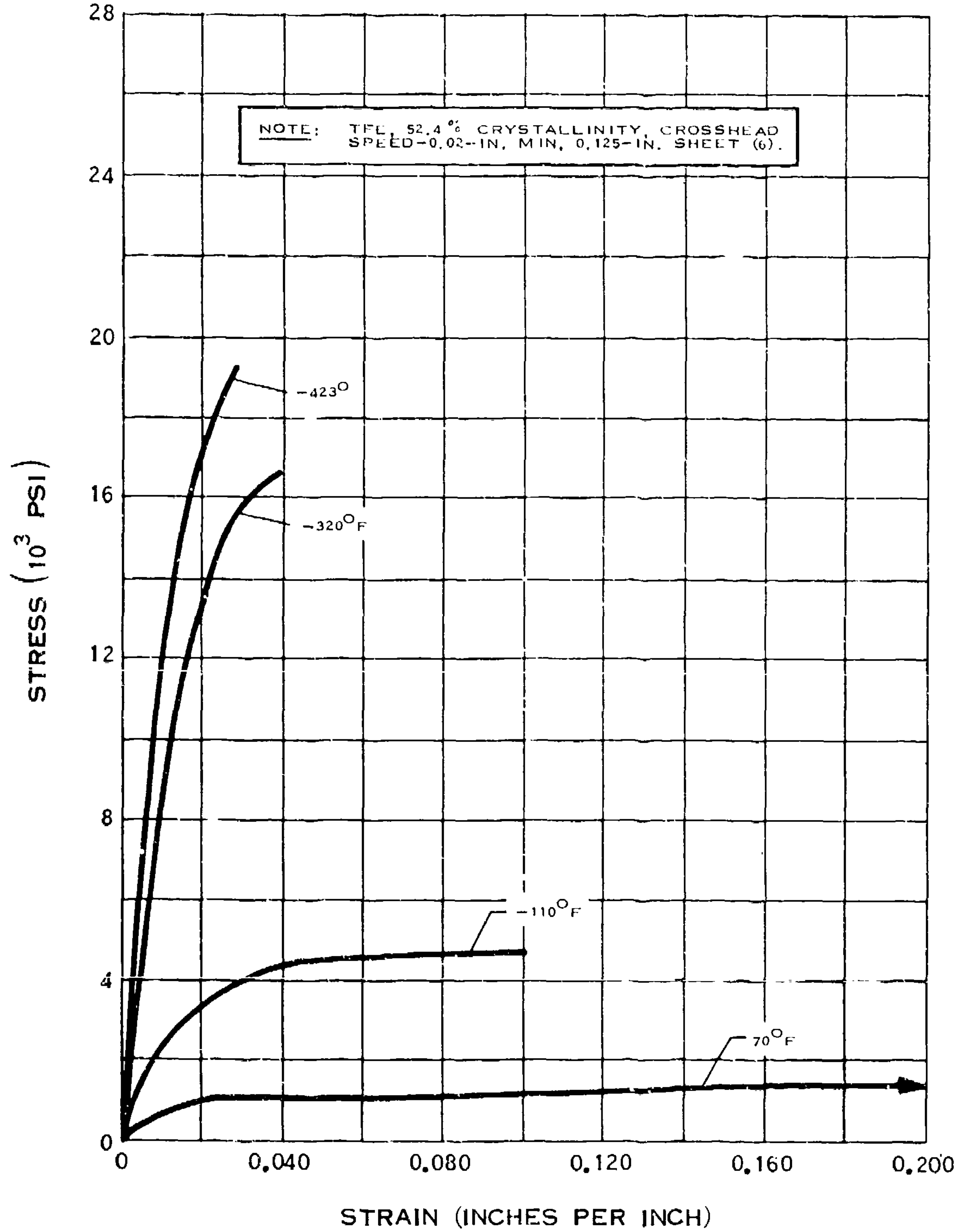
(1–65)



STRESS-STRAIN DIAGRAM FOR TEFLON*

*T.M.
E. I. DUPONT DE NEMOURS AND CO.

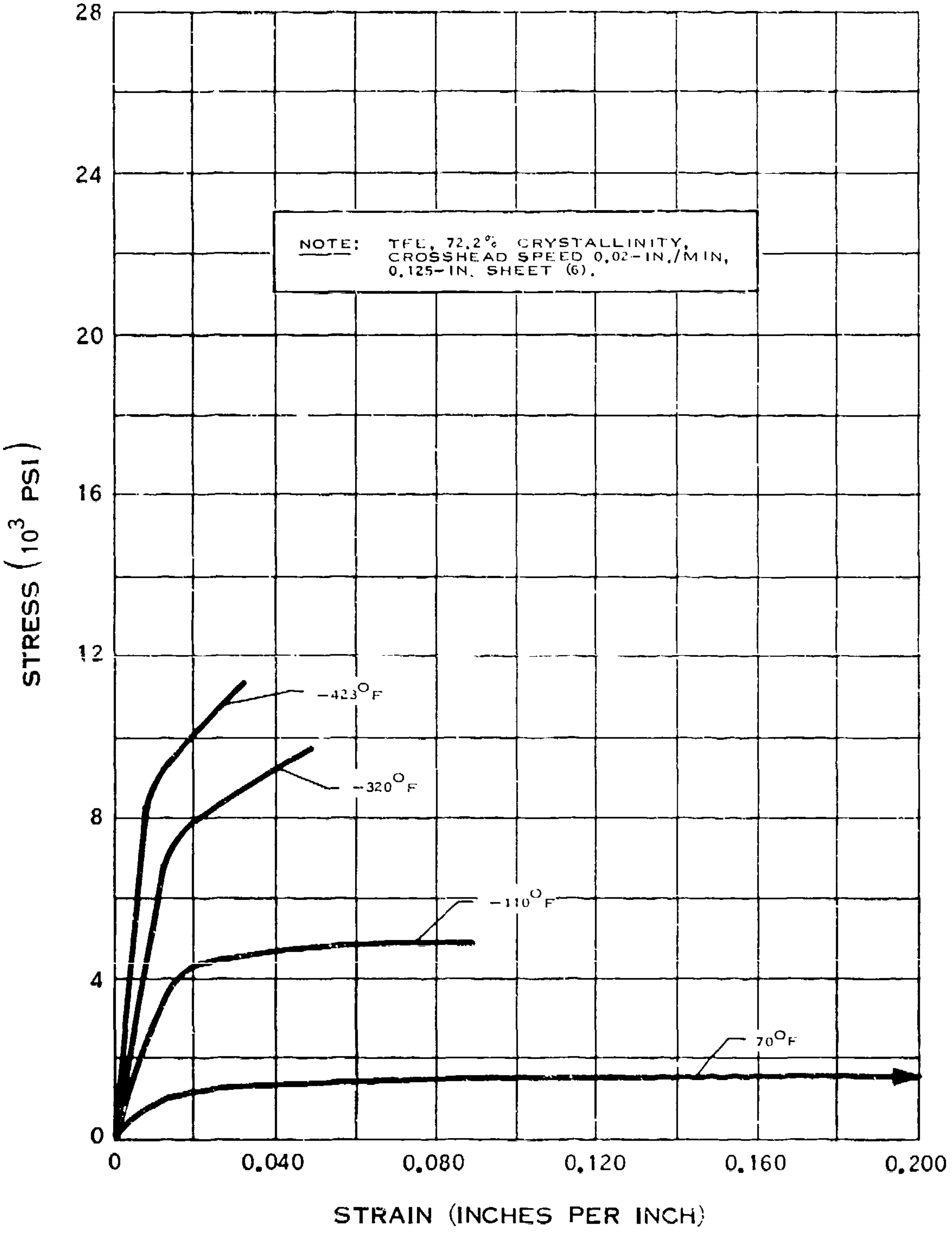
(1-65)



STRESS-STRAIN DIAGRAM FOR TEFLON*

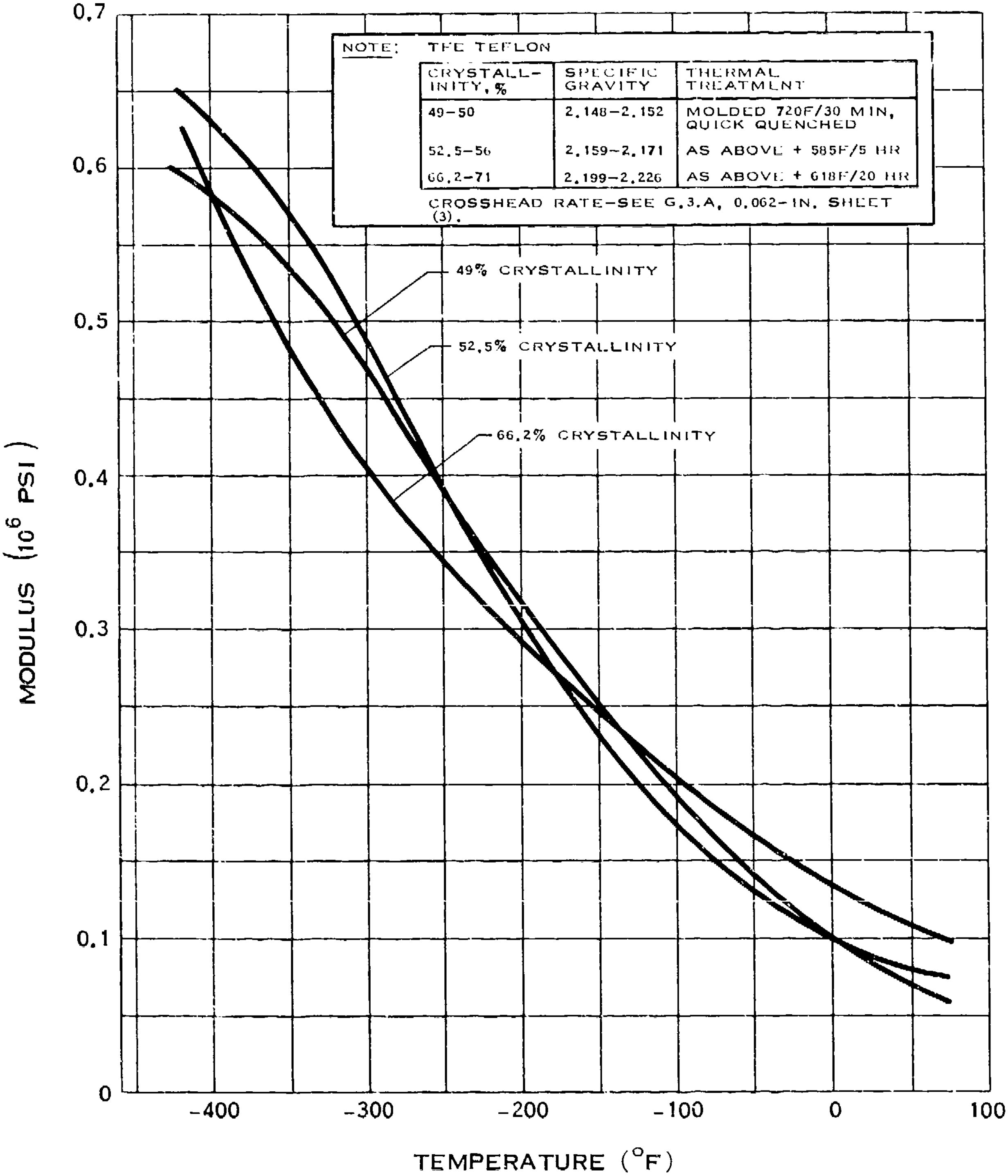
* T.M.
E. I. DUPONT DE NEMOURS AND CO.

(1-65)



STRESS-STRAIN DIAGRAM FOR TEFLON*

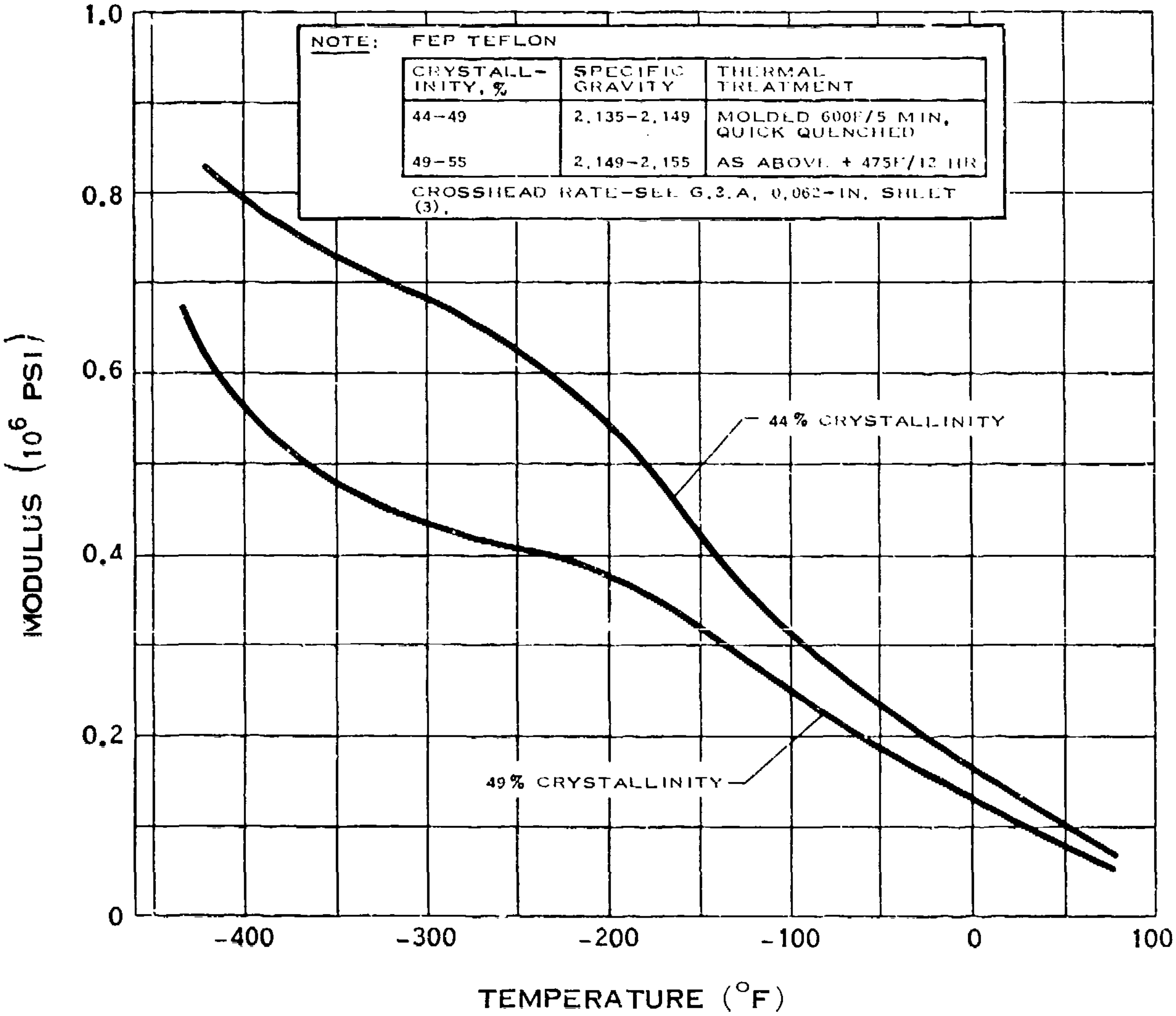
*T.M. E. I. DUPONT DE NEMOURS AND CO.



MODULUS OF ELASTICITY OF TEFLON*

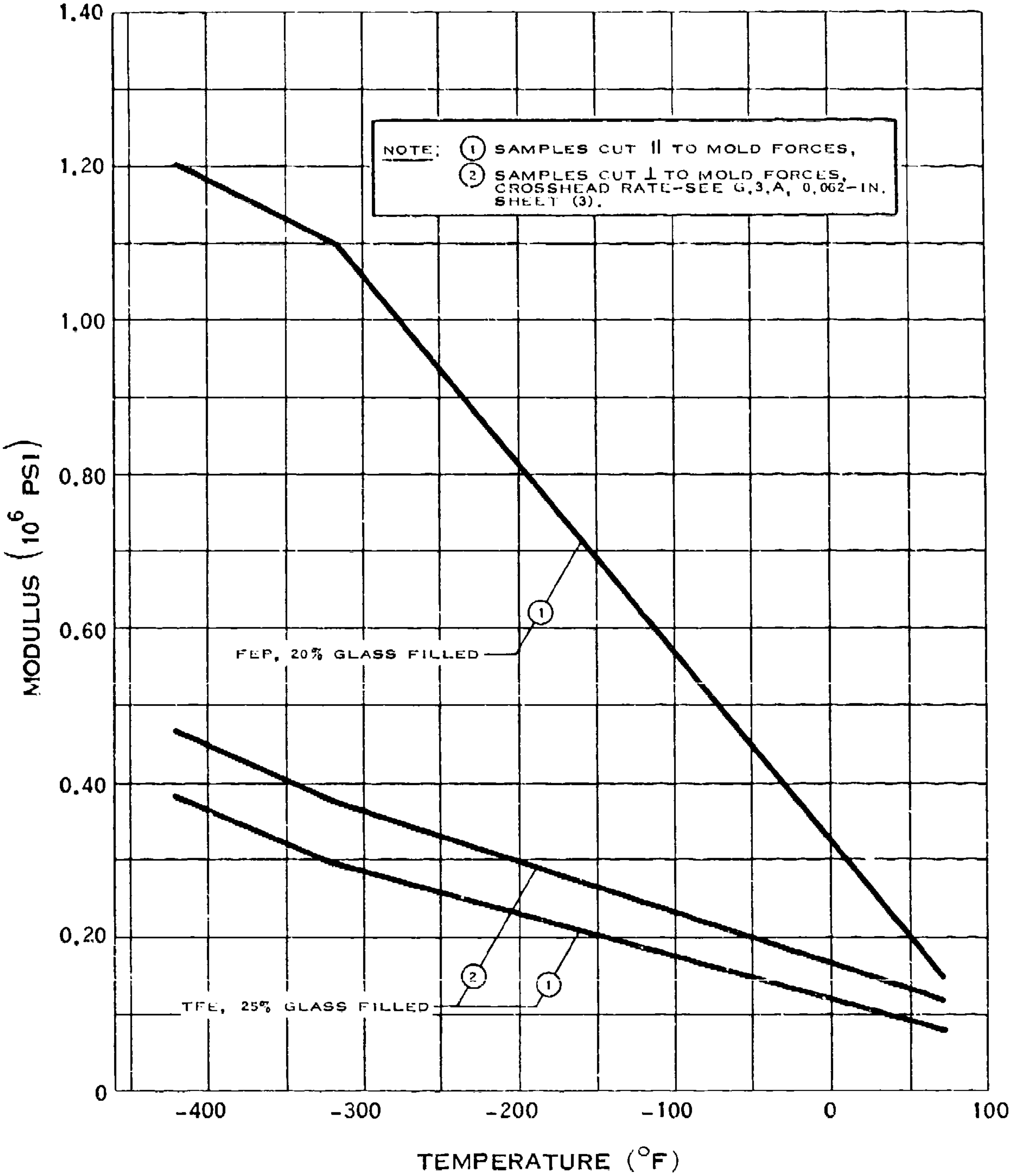
* T.M. E. I. DUPONT DE NEMOURS AND CO.

G.3.i-1



MODULUS OF ELASTICITY OF TEFLON*

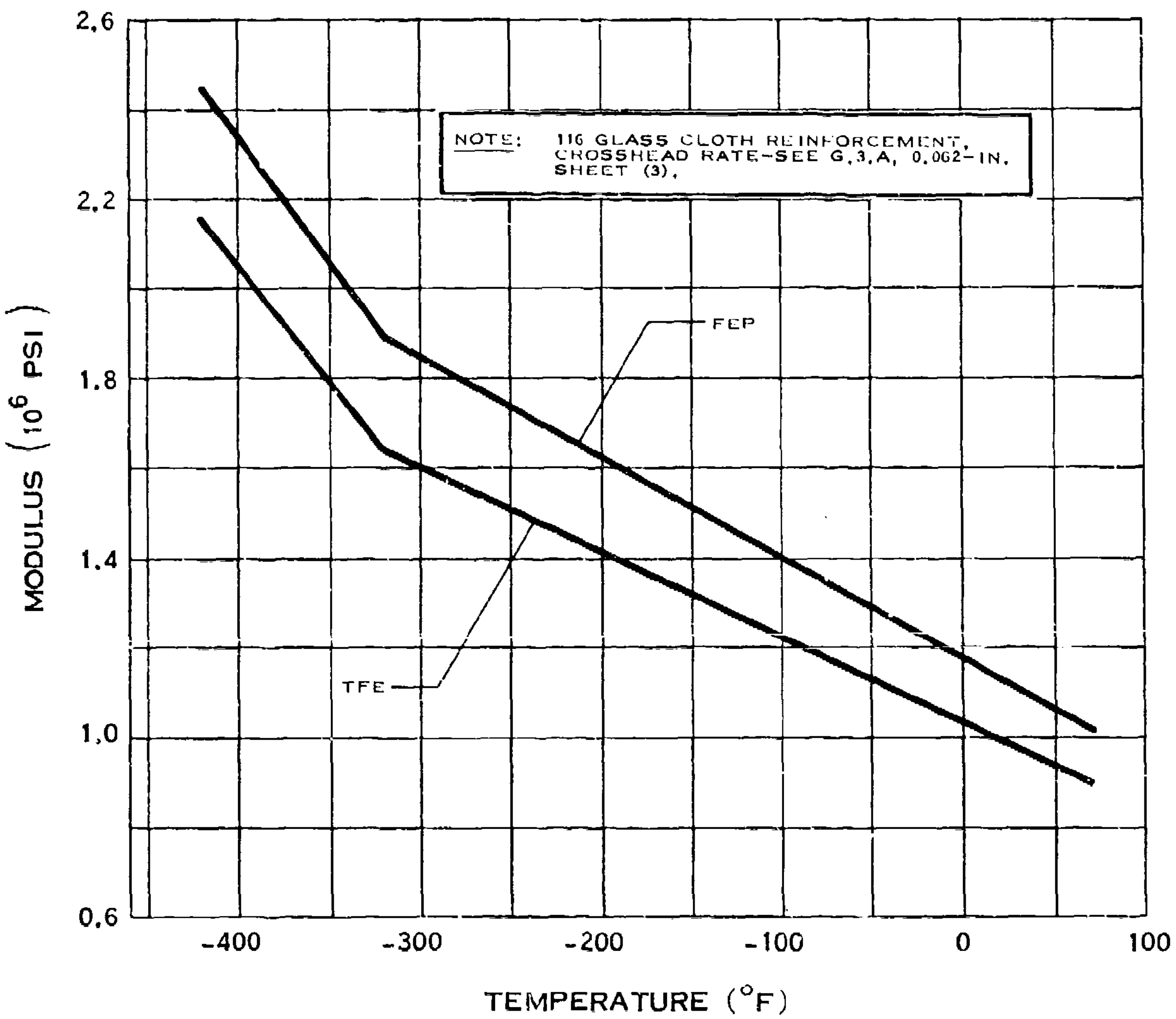
* T.M.
E. I. DUPONT DE NEMOURS AND CO.



MODULUS OF ELASTICITY OF TEFLON*

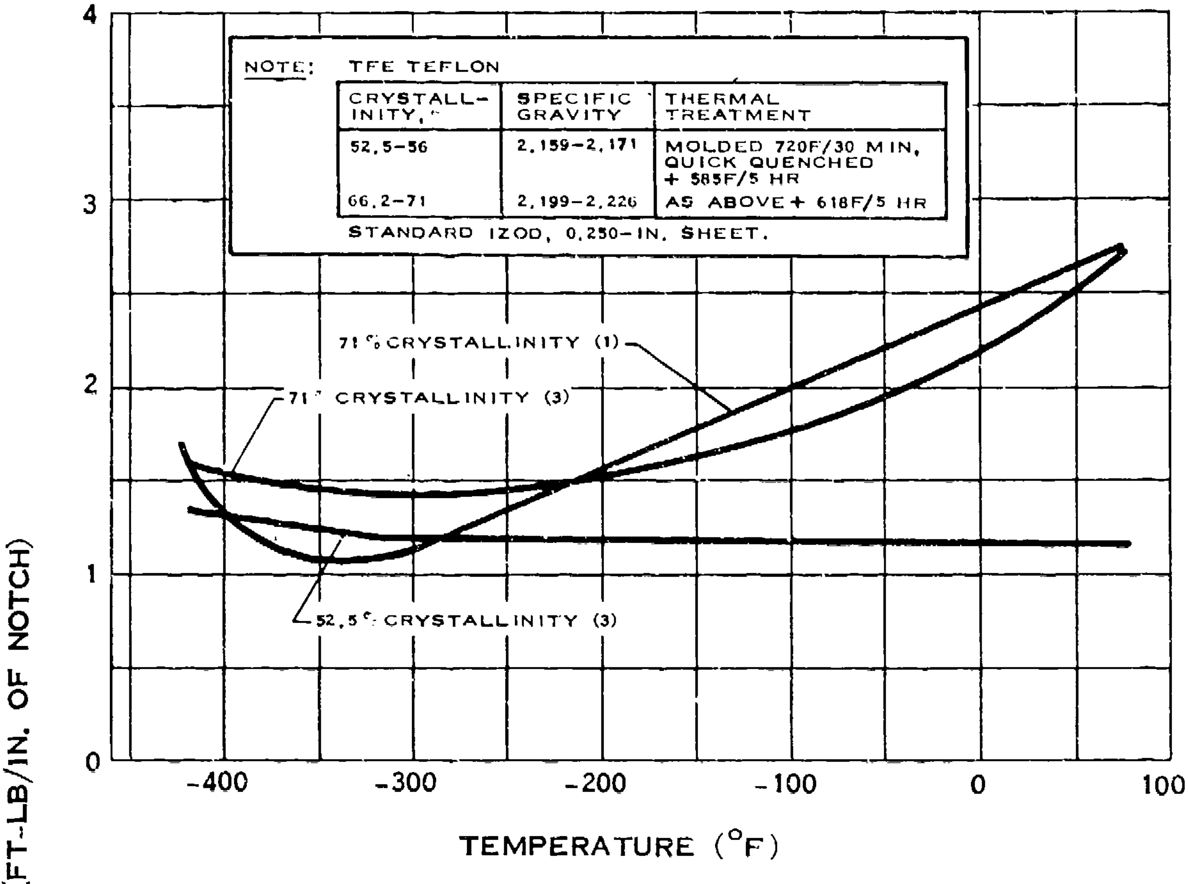
* T.M.
E. I. DUPONT DE NEMOURS AND CO.

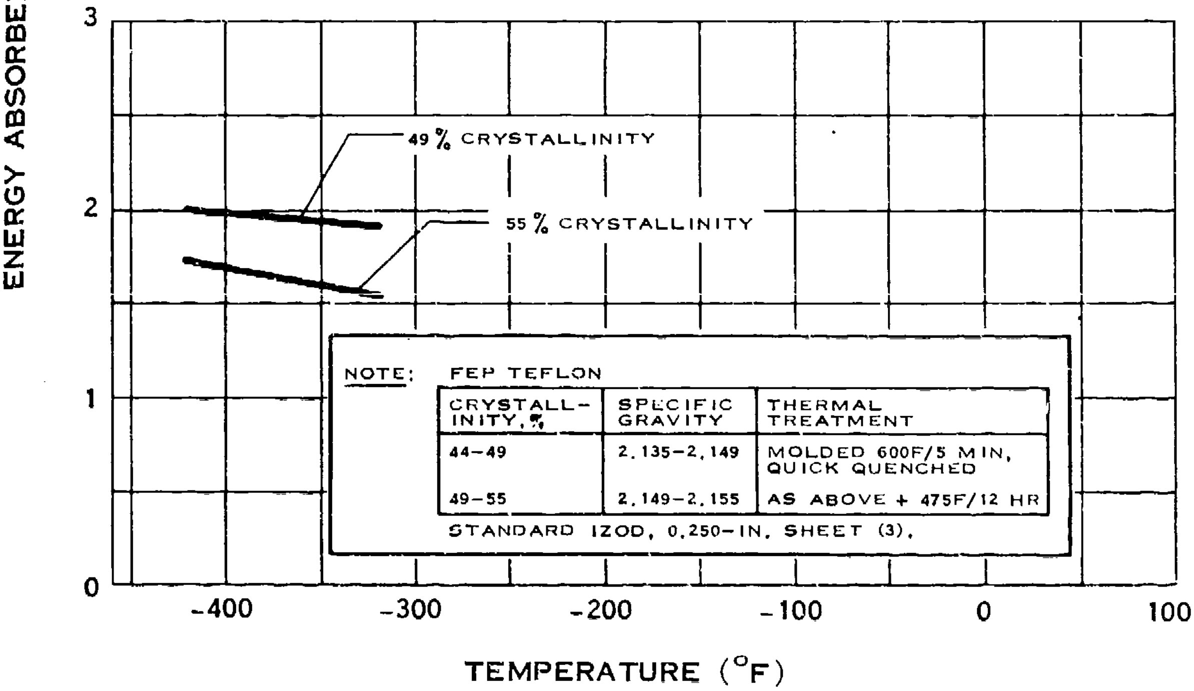
(7-64)



MODULUS OF ELASTICITY OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

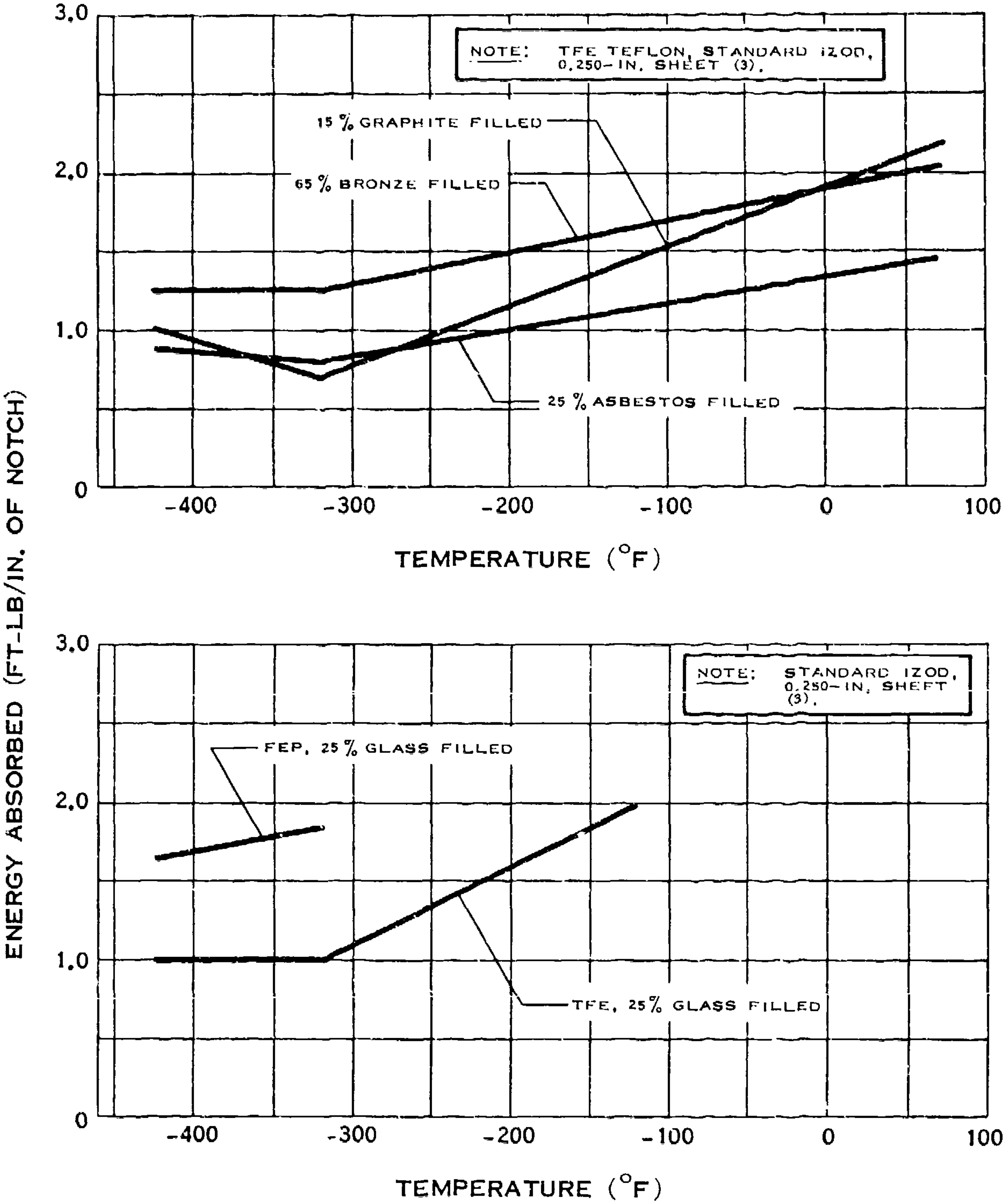




IMPACT STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

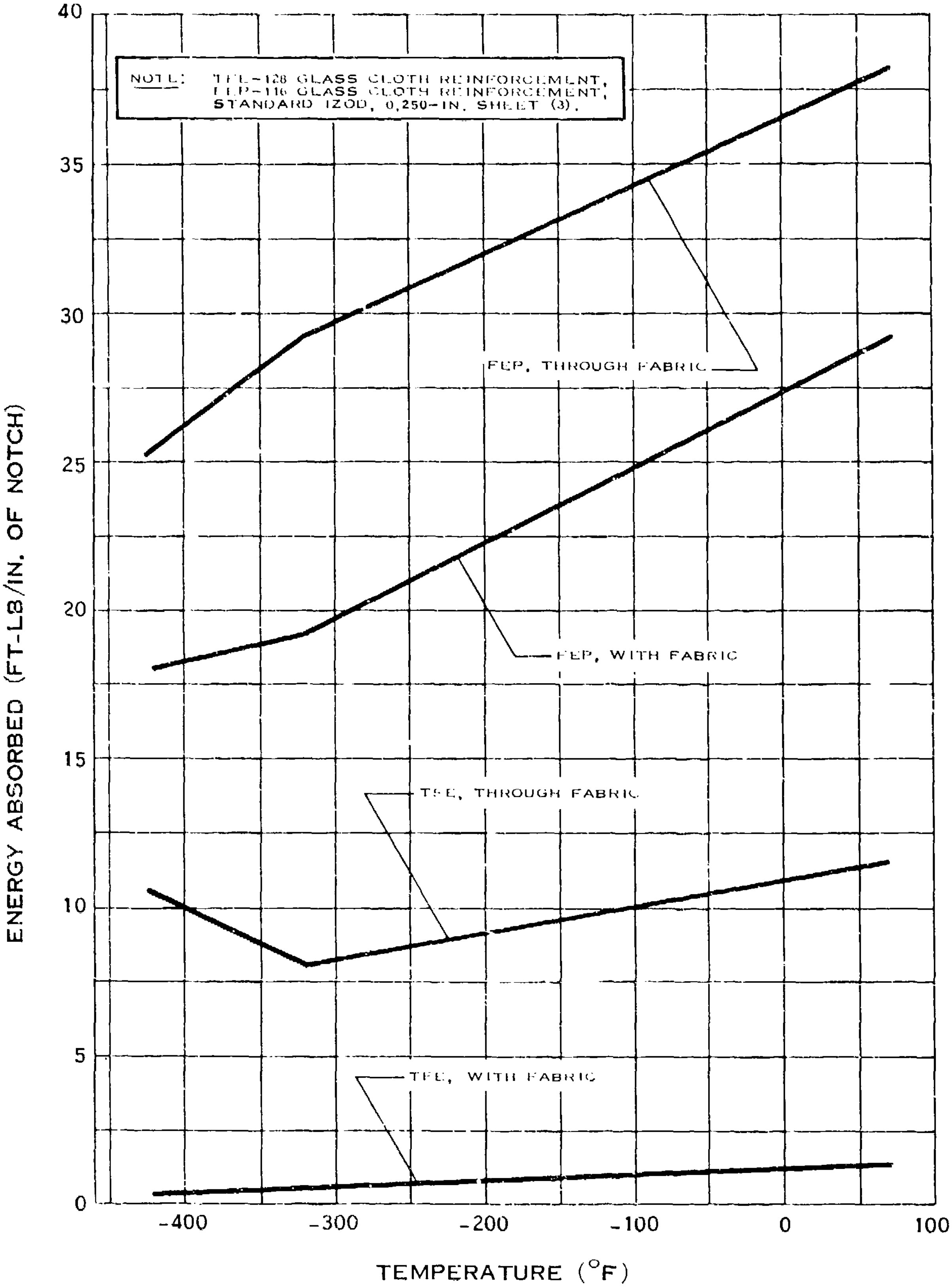
(7-65)



IMPACT STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

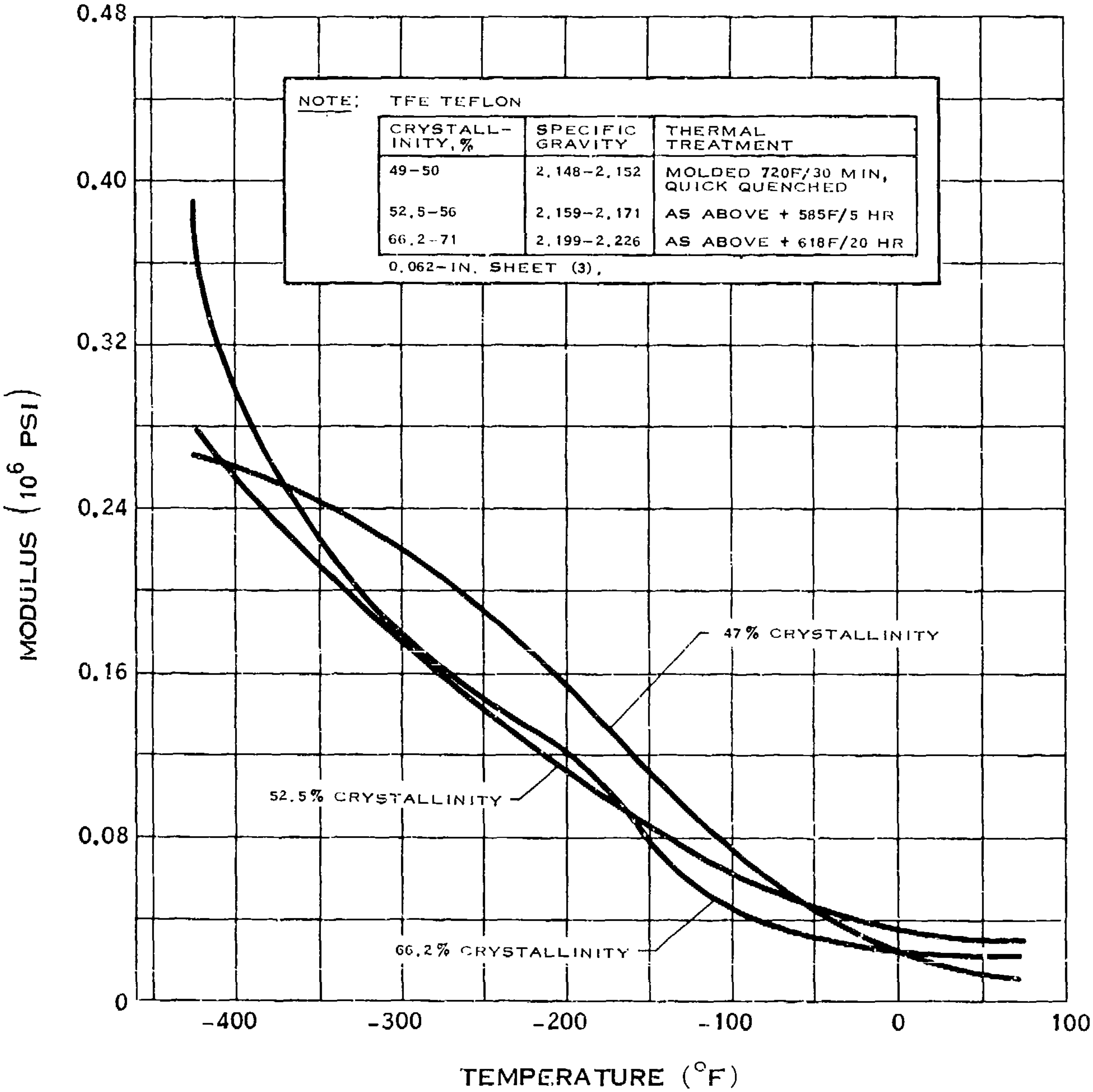
(7-64)



IMPACT STRENGTH OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

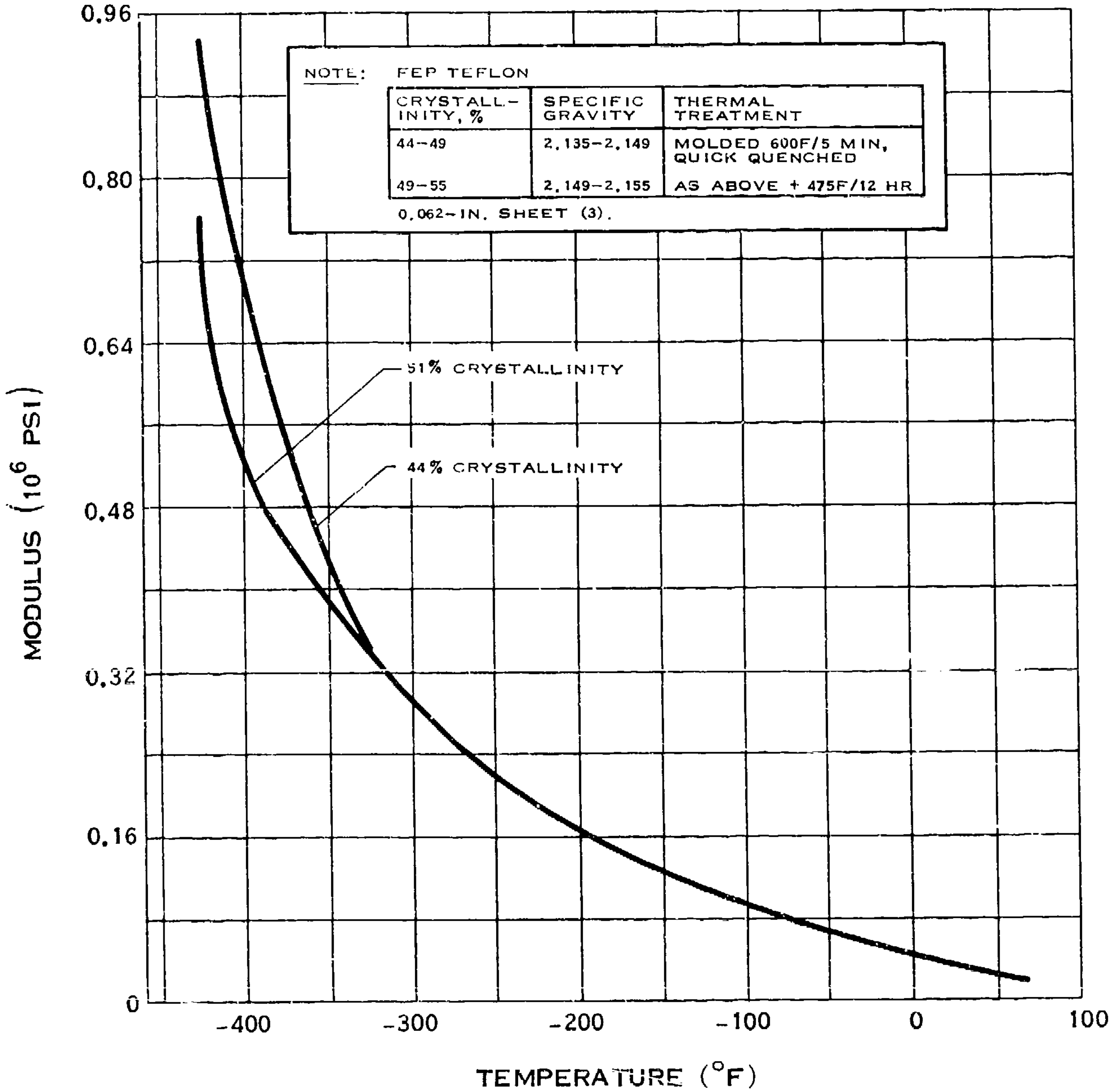
(7-64)



MODULUS OF RIGIDITY OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

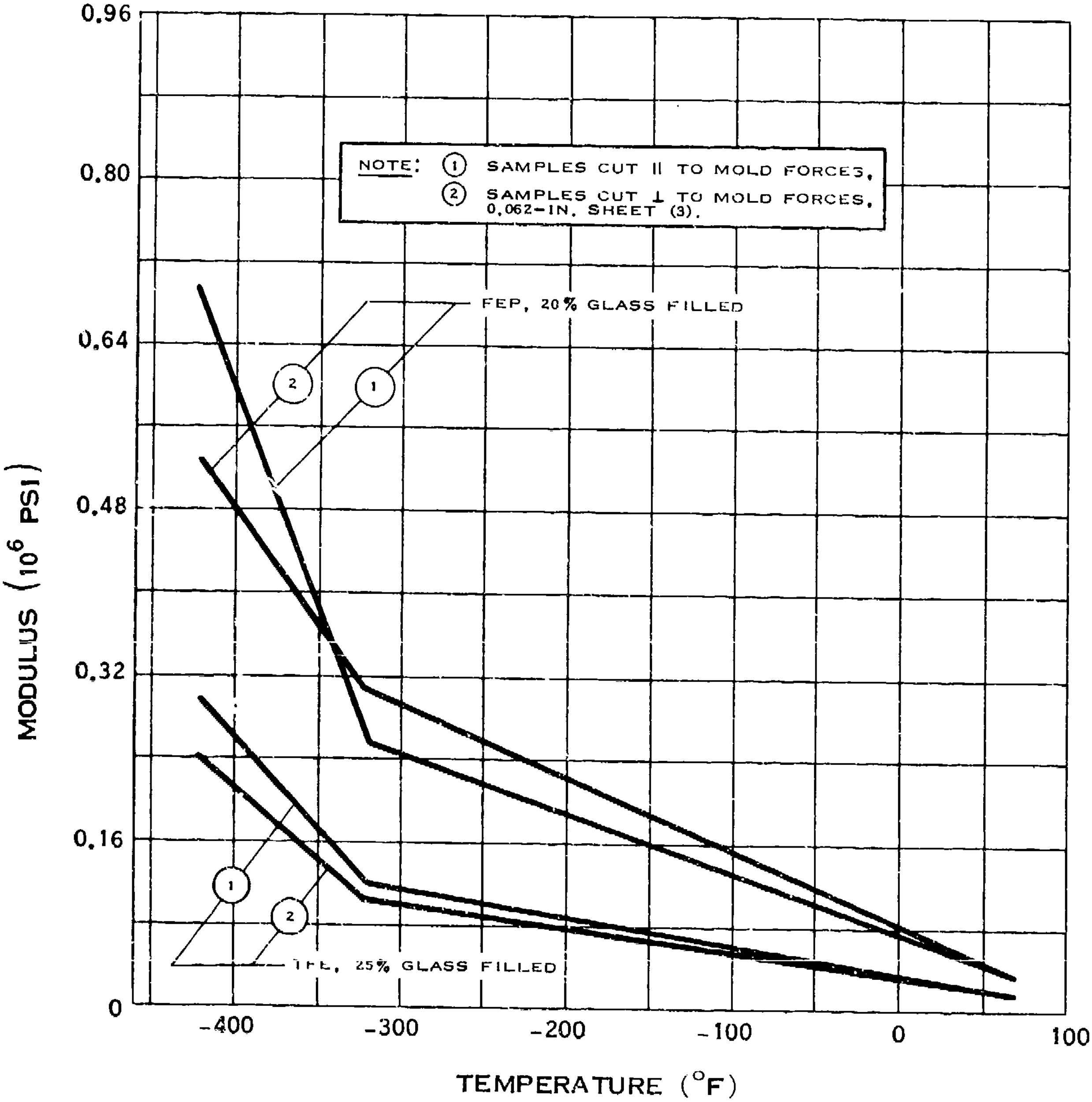
G.3.ℓ-1



MODULUS OF RIGIDITY OF TEFLON*

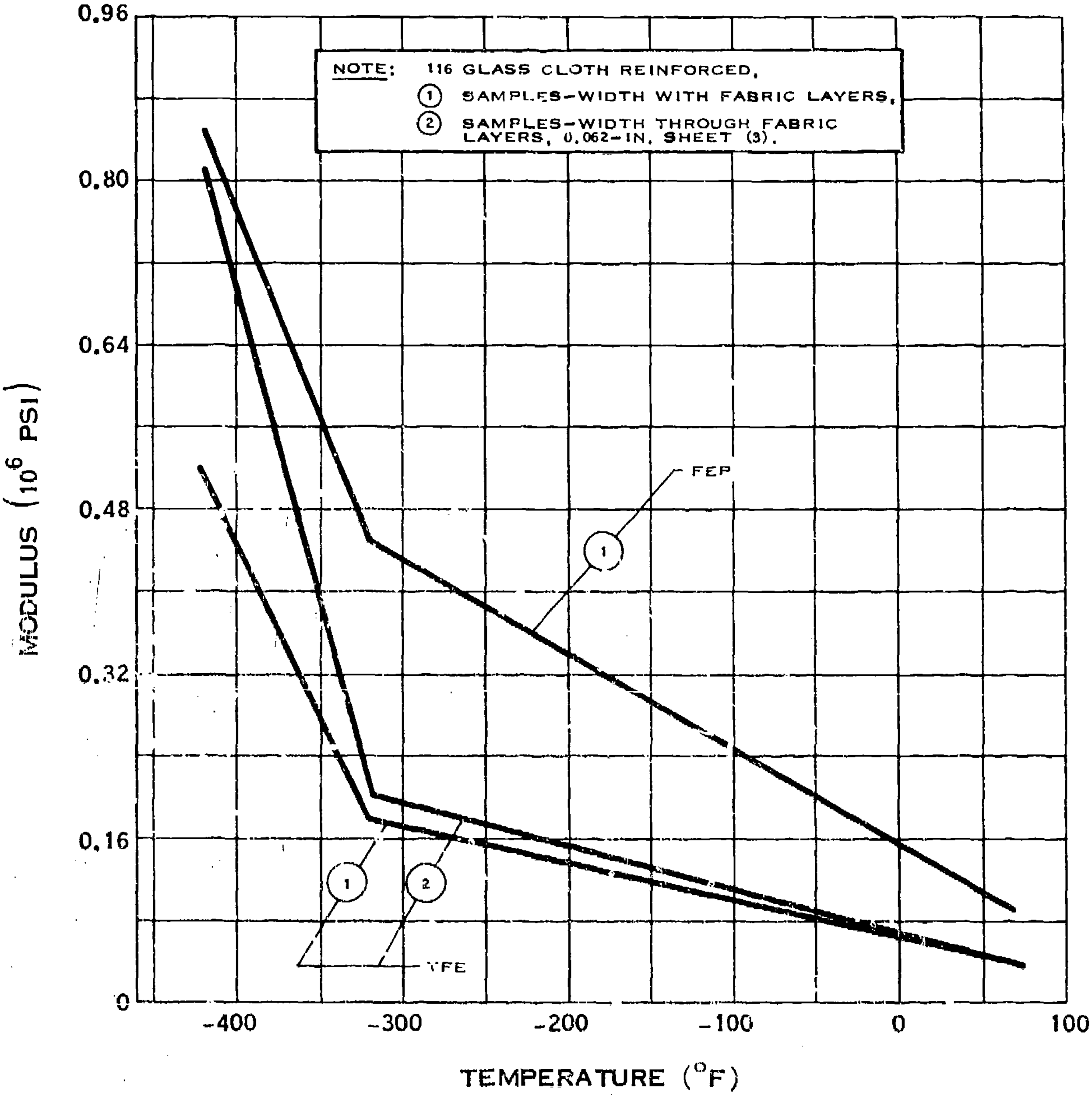
* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)



MODULUS OF RIGIDITY OF TEFLON*

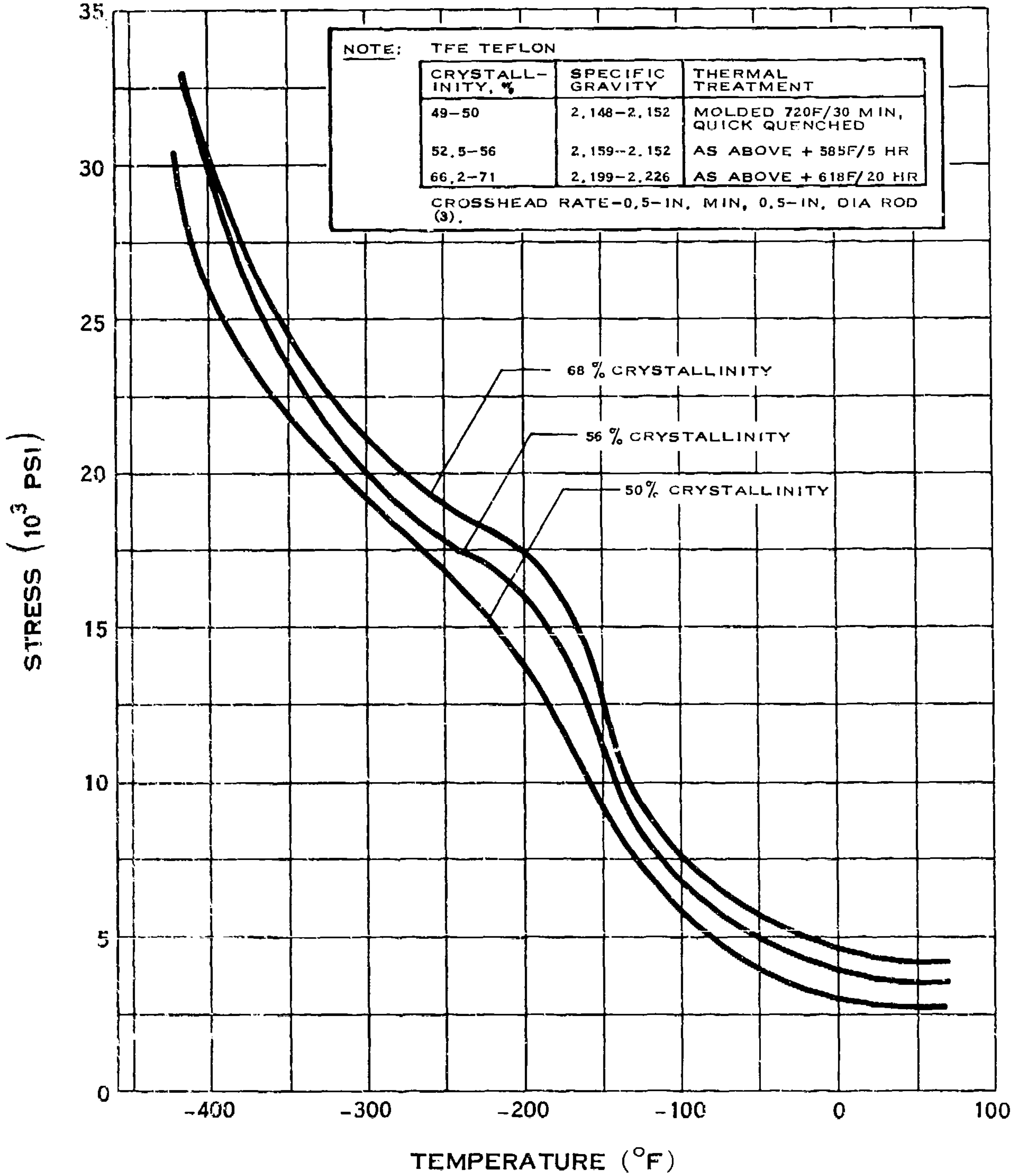
*T.M. E. I. DUPONT DE NEMOURS AND CO.



MODULUS OF RIGIDITY OF TEFLON*

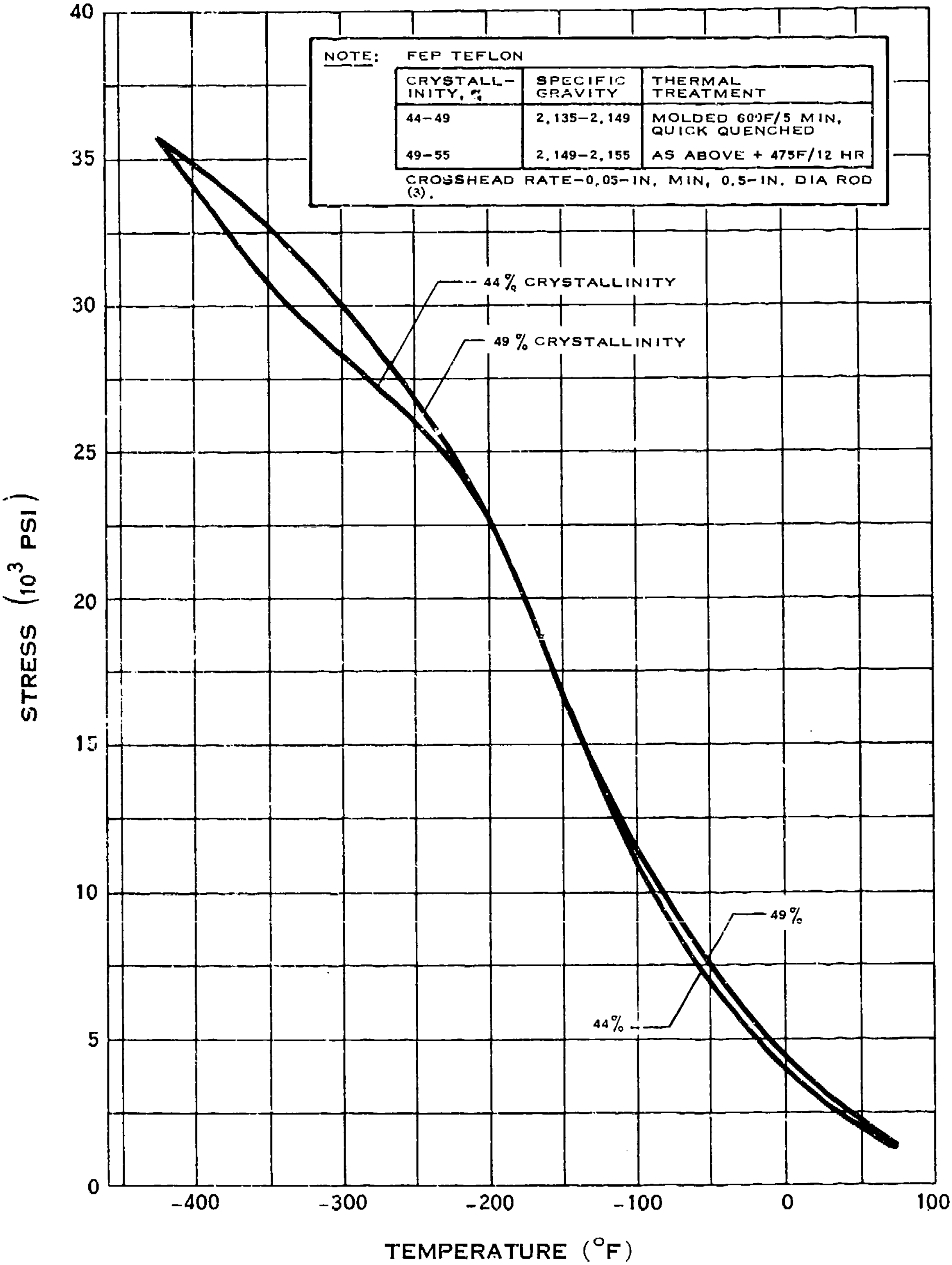
* T.M. E. I. DUPONT DE NEMOURS AND CO.

G.3.m



COMPRESSIVE STRENGTH OF TEFLON*

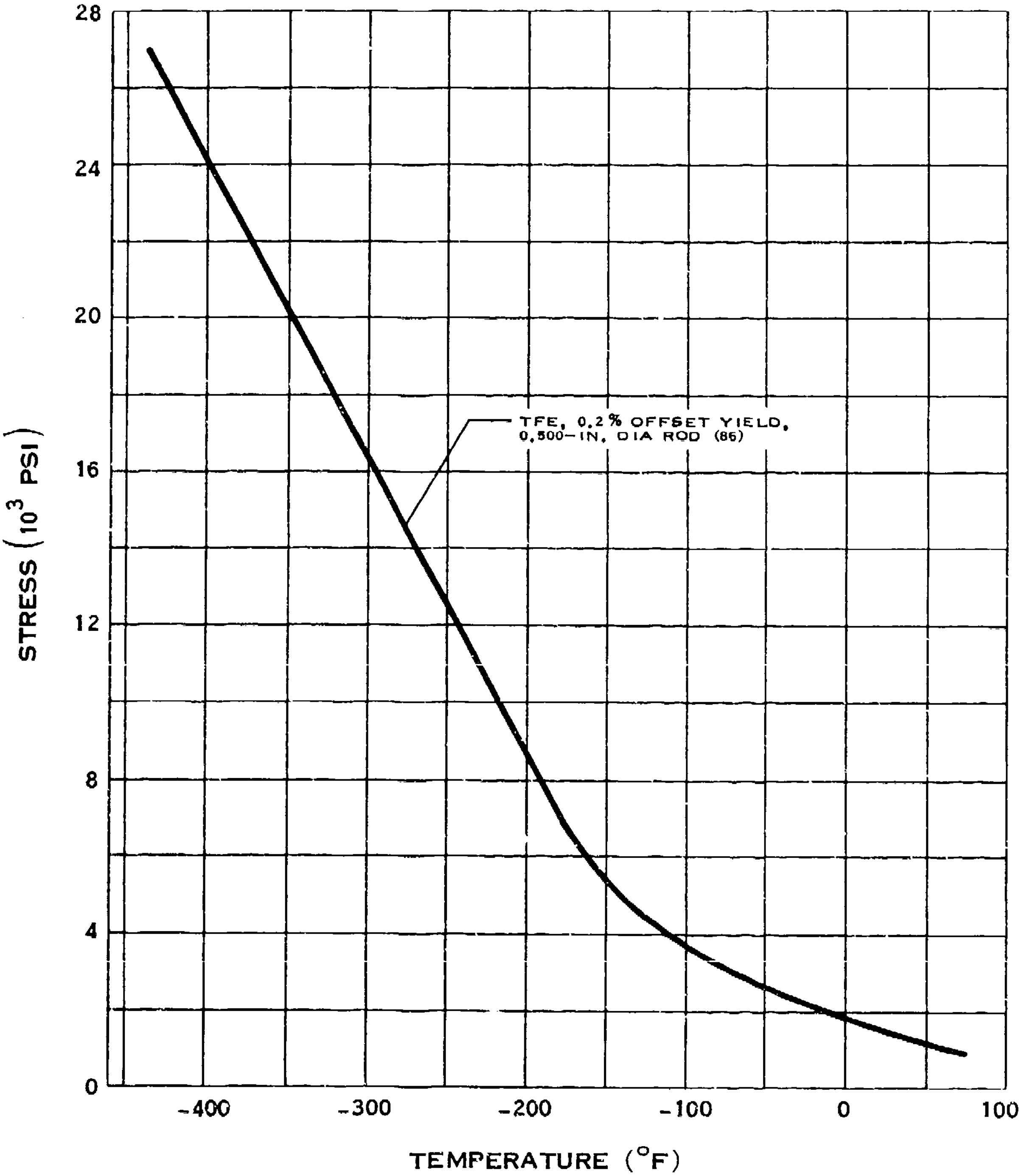
* T.M. E. I. DUPONT DE NEMOURS AND CO.



COMPRESSIVE STRENGTH OF TEFLON*

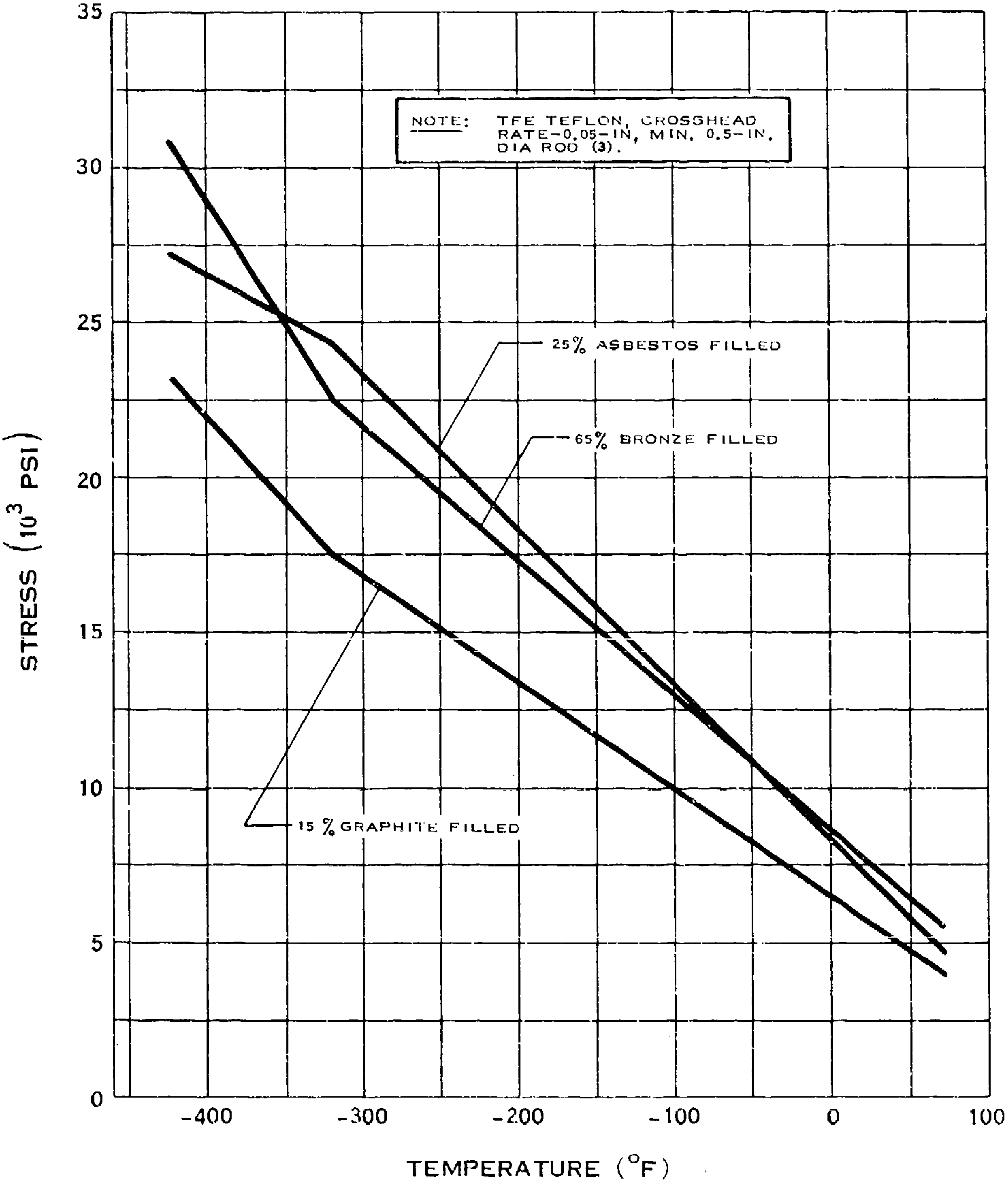
* T.M. E. I. DUPONT DE NEMOURS AND CO.

G.3.m-2



COMPRESSIVE STRENGTH OF TEFLON*

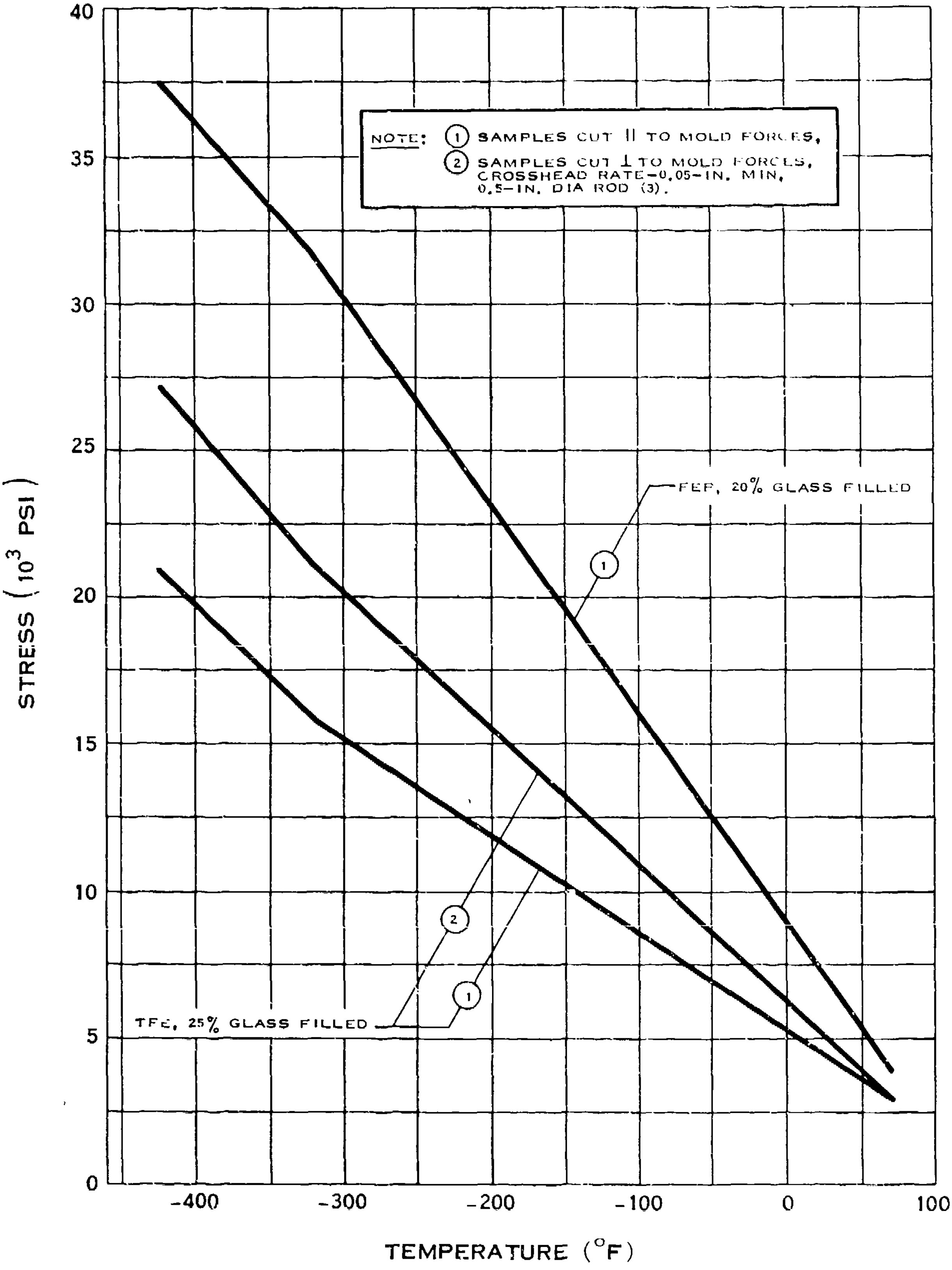
* T.M. E. I. DUPONT DE NEMOURS AND CO.



COMPRESSIVE STRENGTH OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

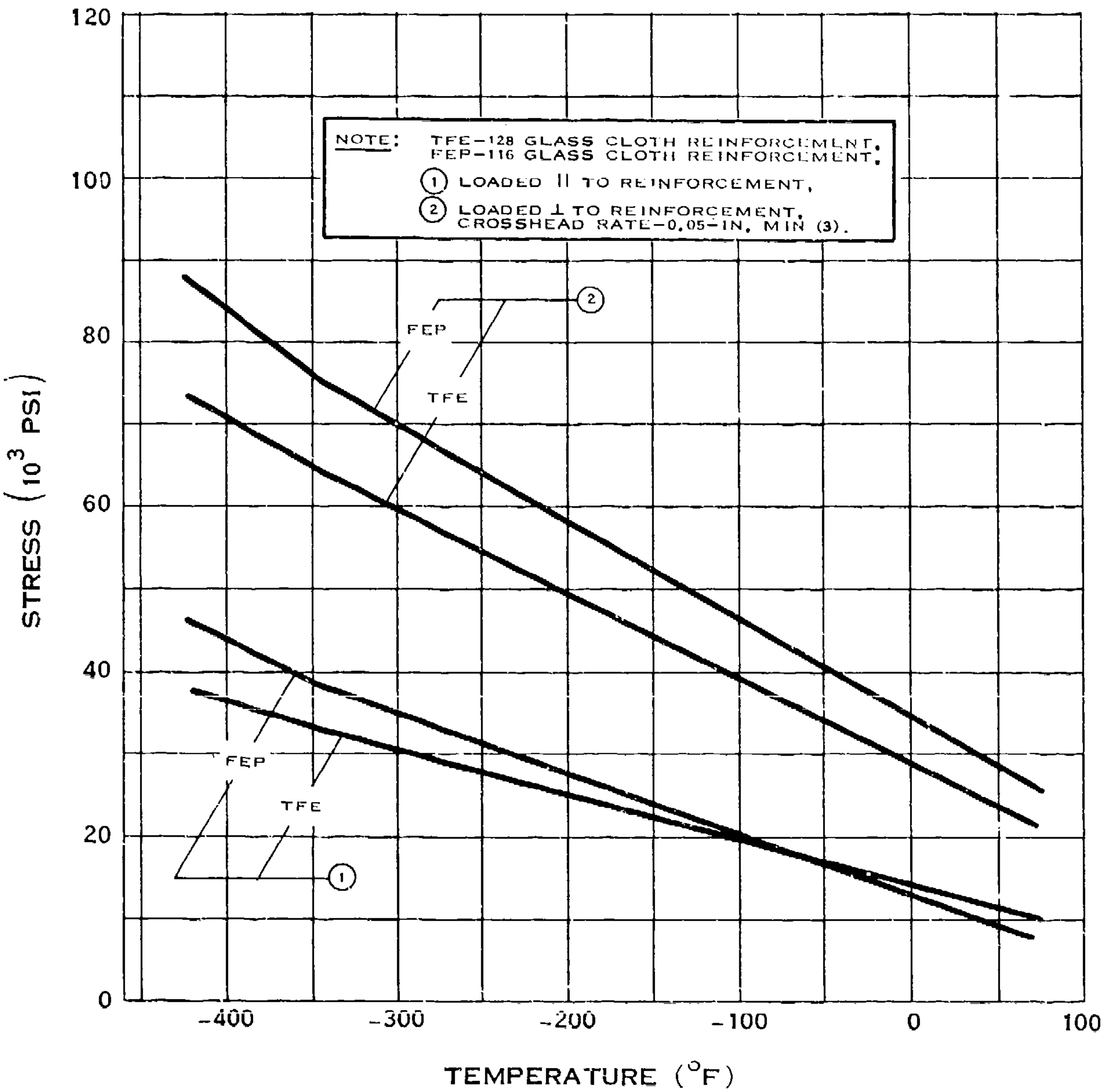
(7-64)



COMPRESSIVE STRENGTH OF TEFLON*

*T.M.
E. I. DUPONT DE NEMOURS AND CO.

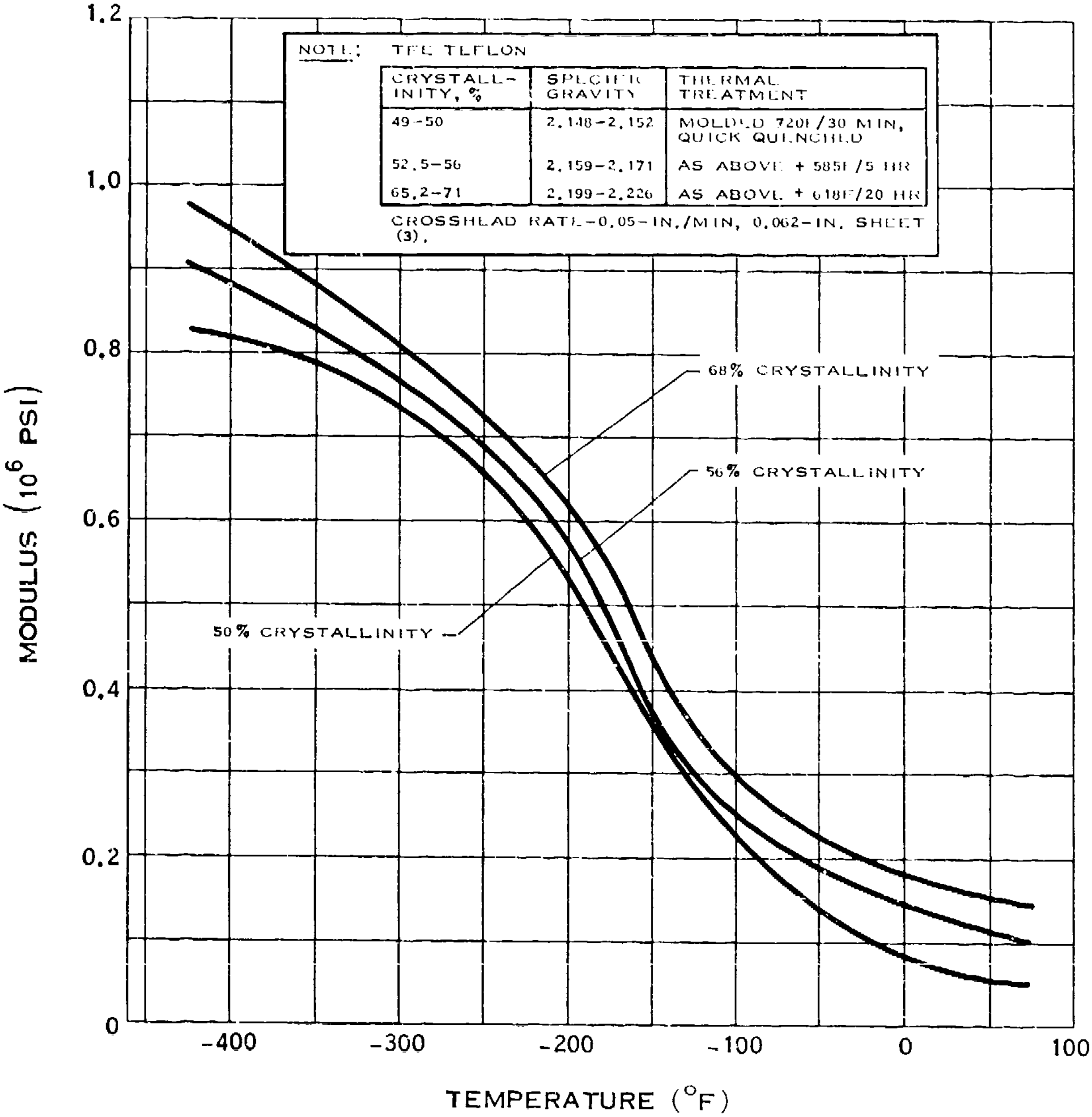
(7-64)



COMPRESSIVE STRENGTH OF TEFLON*

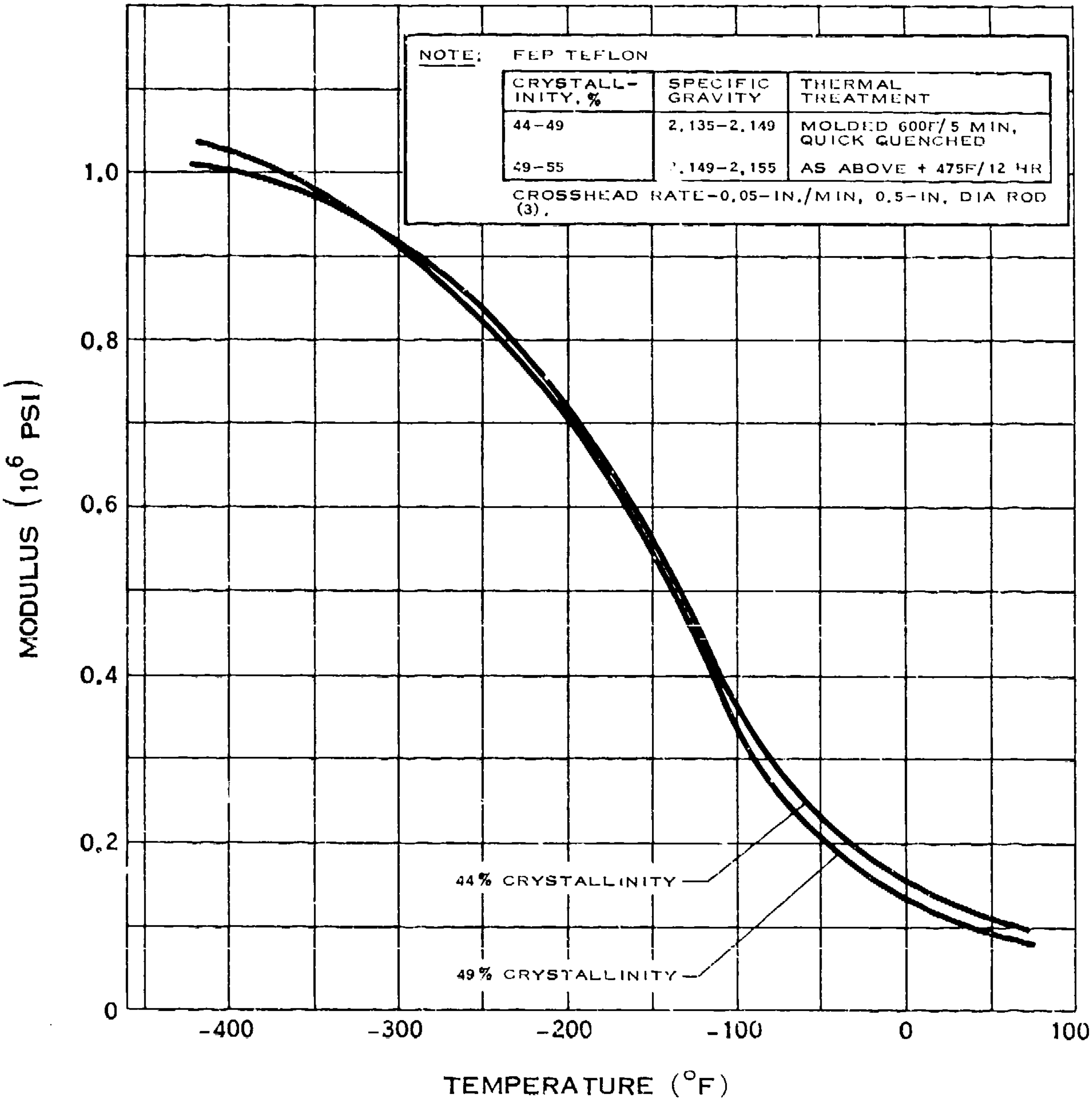
*T.M.
E. I. DUPONT DE NEMOURS AND CO.

G.3.n



COMPRESSIVE MODULUS OF TEFLON*

*T.M. E. I. DUPONT DE NEMOURS AND CO.

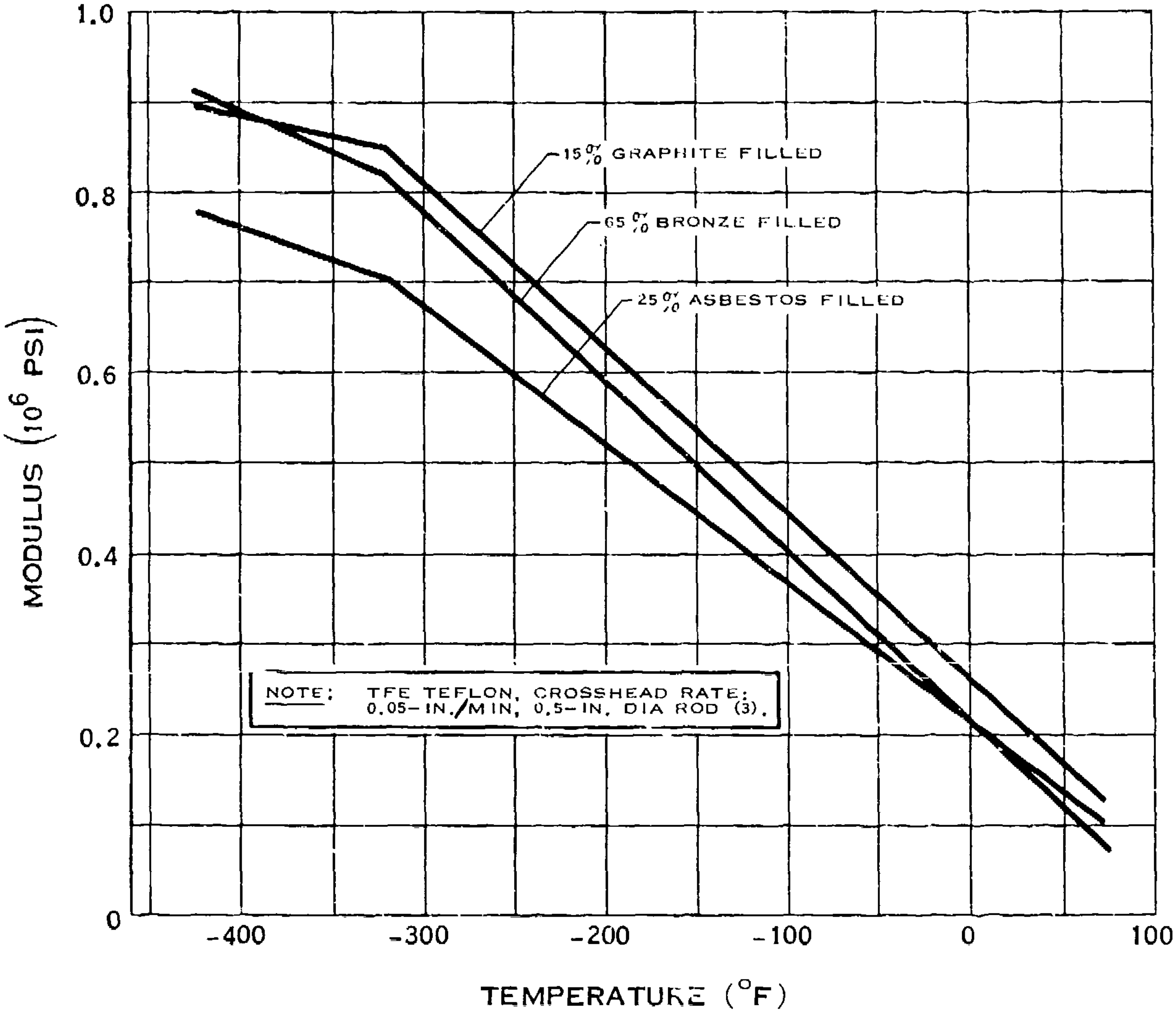


COMPRESSIVE MODULUS OF TEFLON*

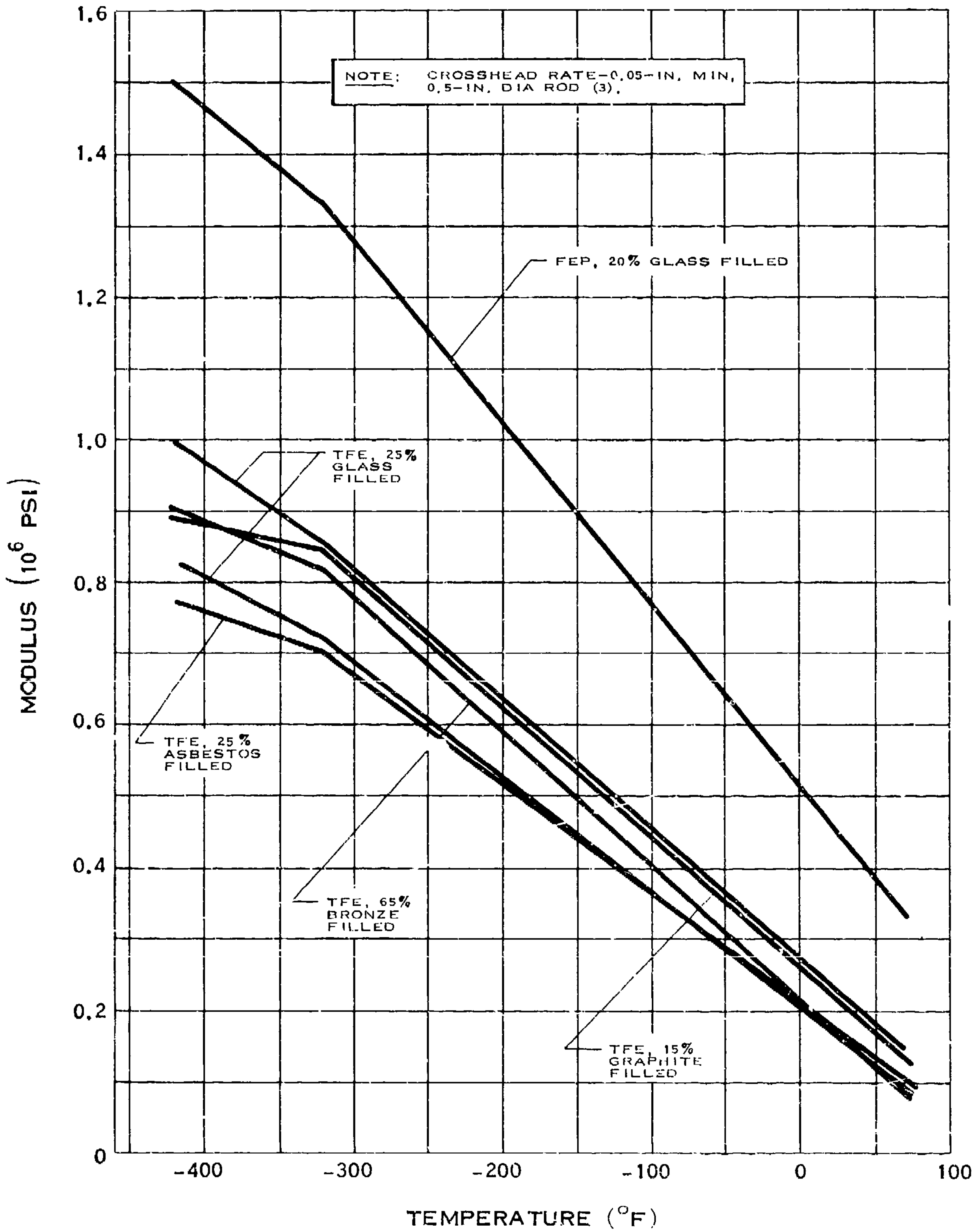
* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

G.3.n-2



COMPRESSIVE MODULUS OF TEFLON

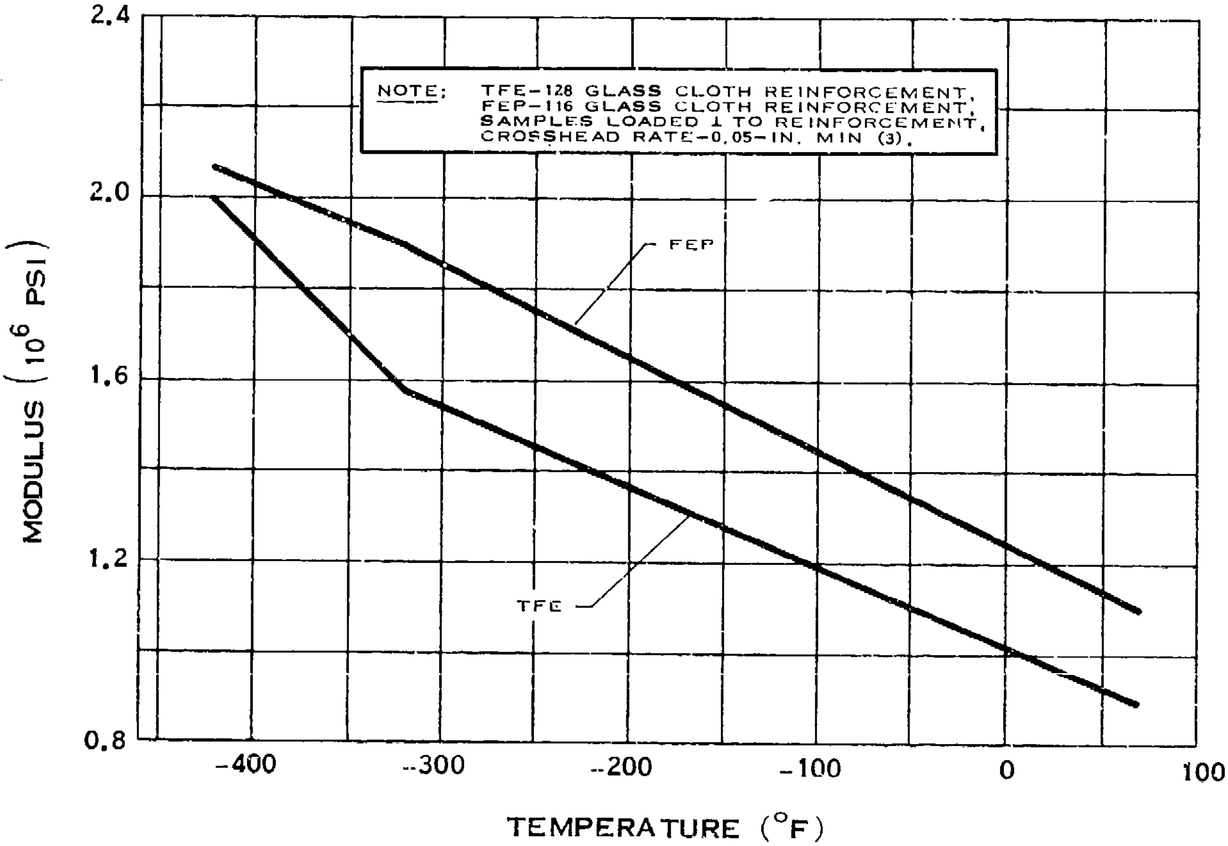


COMPRESSIVE MODULUS OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

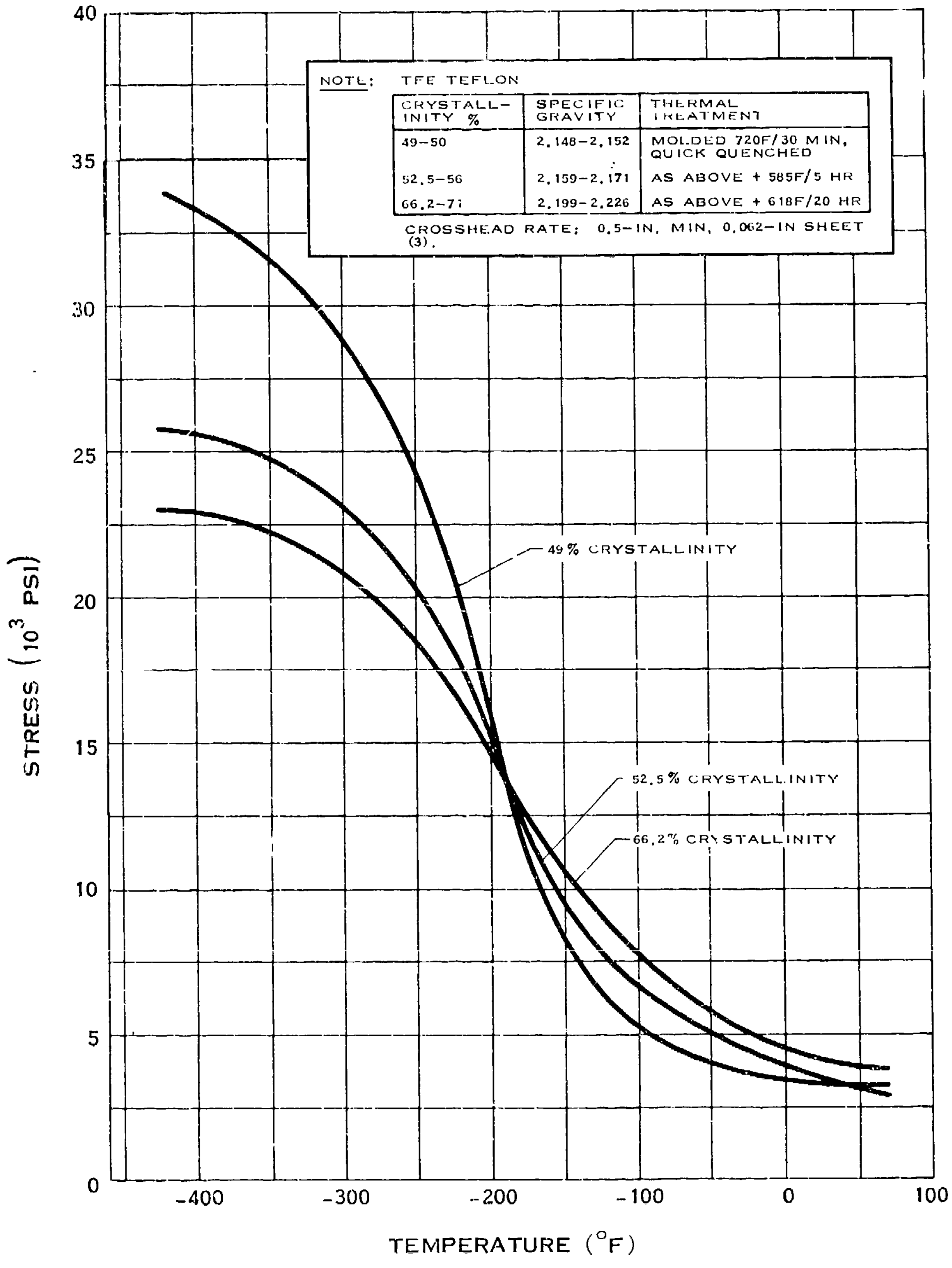
(7-64)

G.3.n-4



COMPRESSIVE MODULUS OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

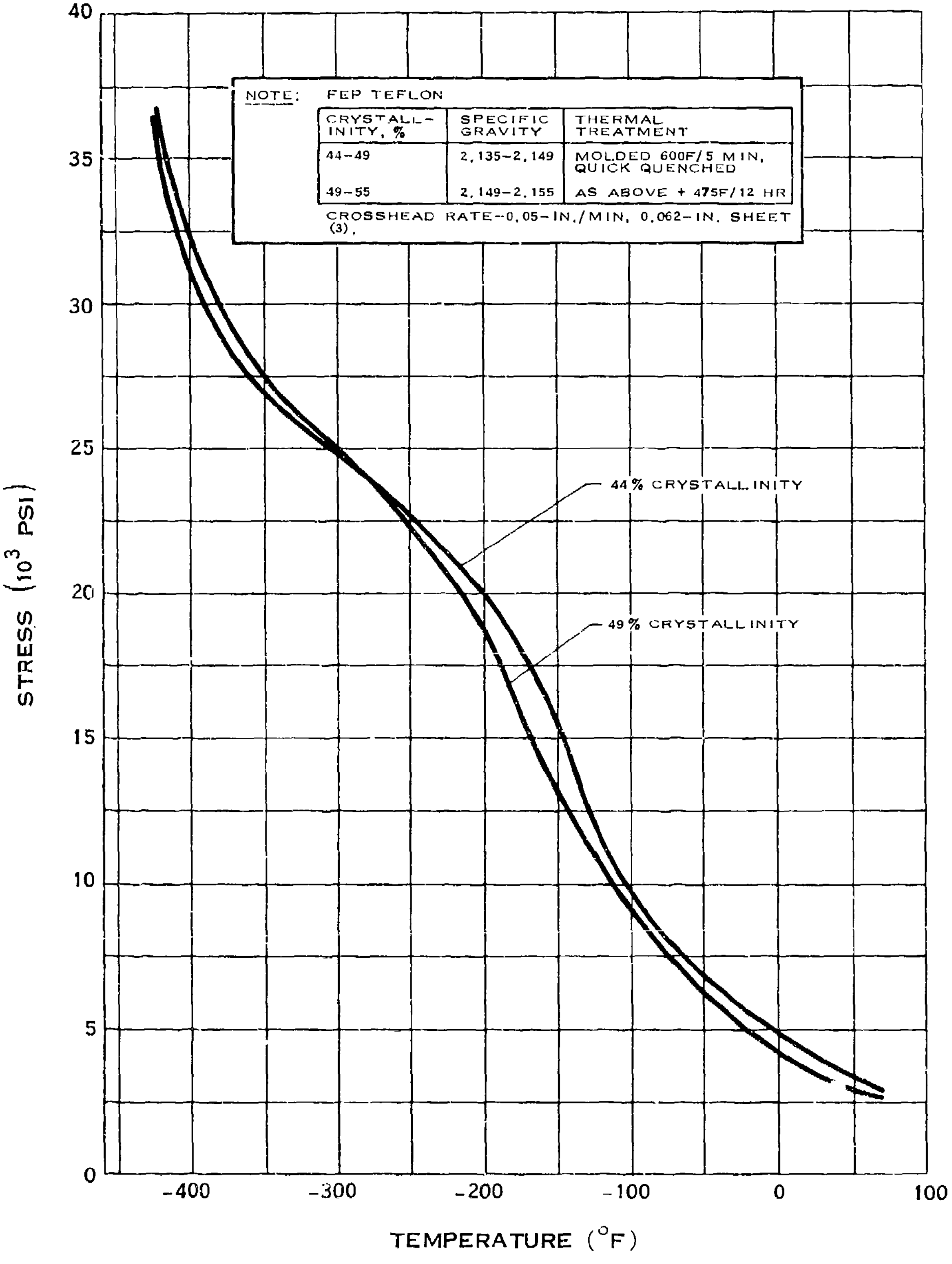


FLEXURAL STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

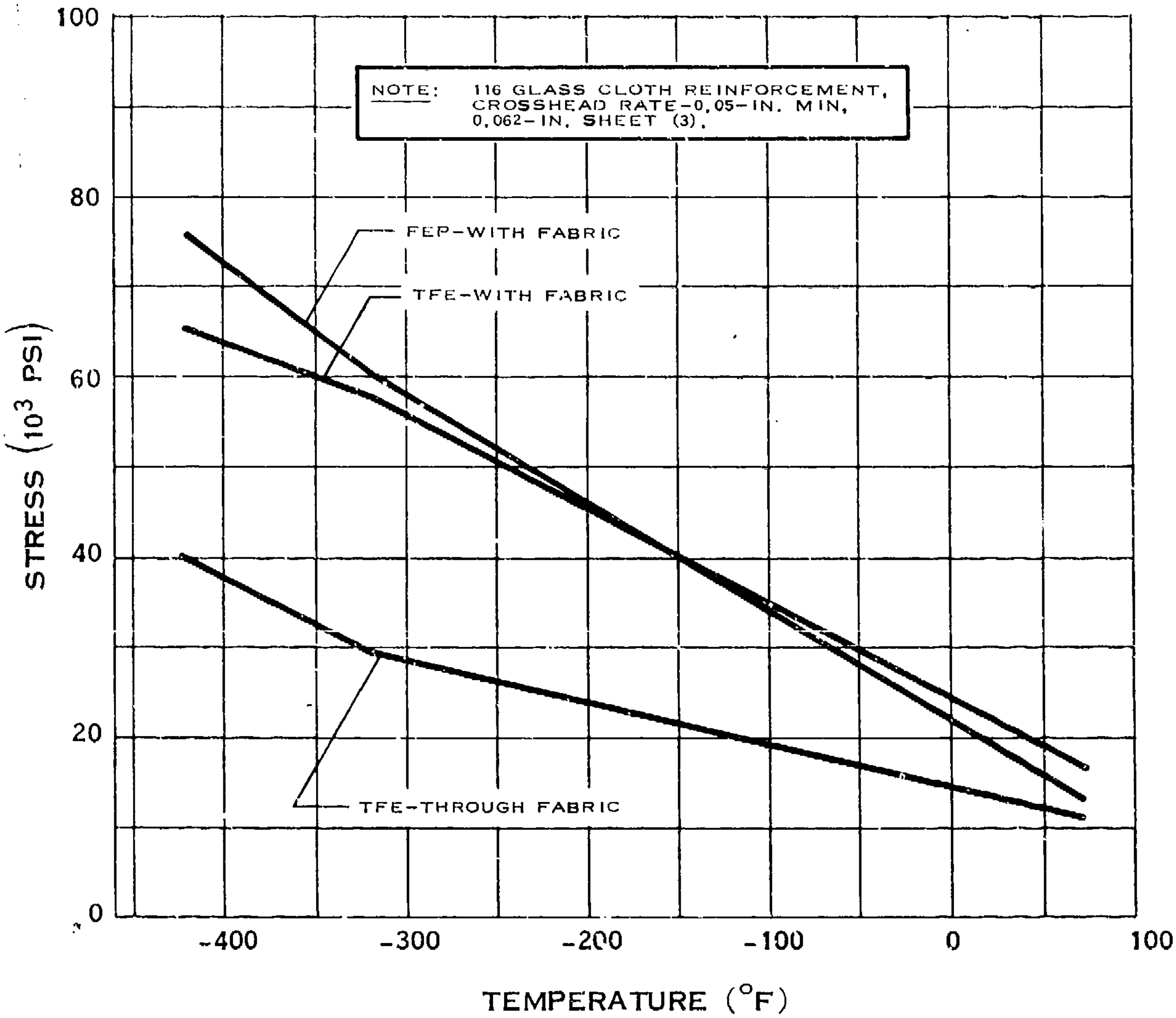
G.3.r-1



FLEXURAL STRENGTH OF TEFLON*

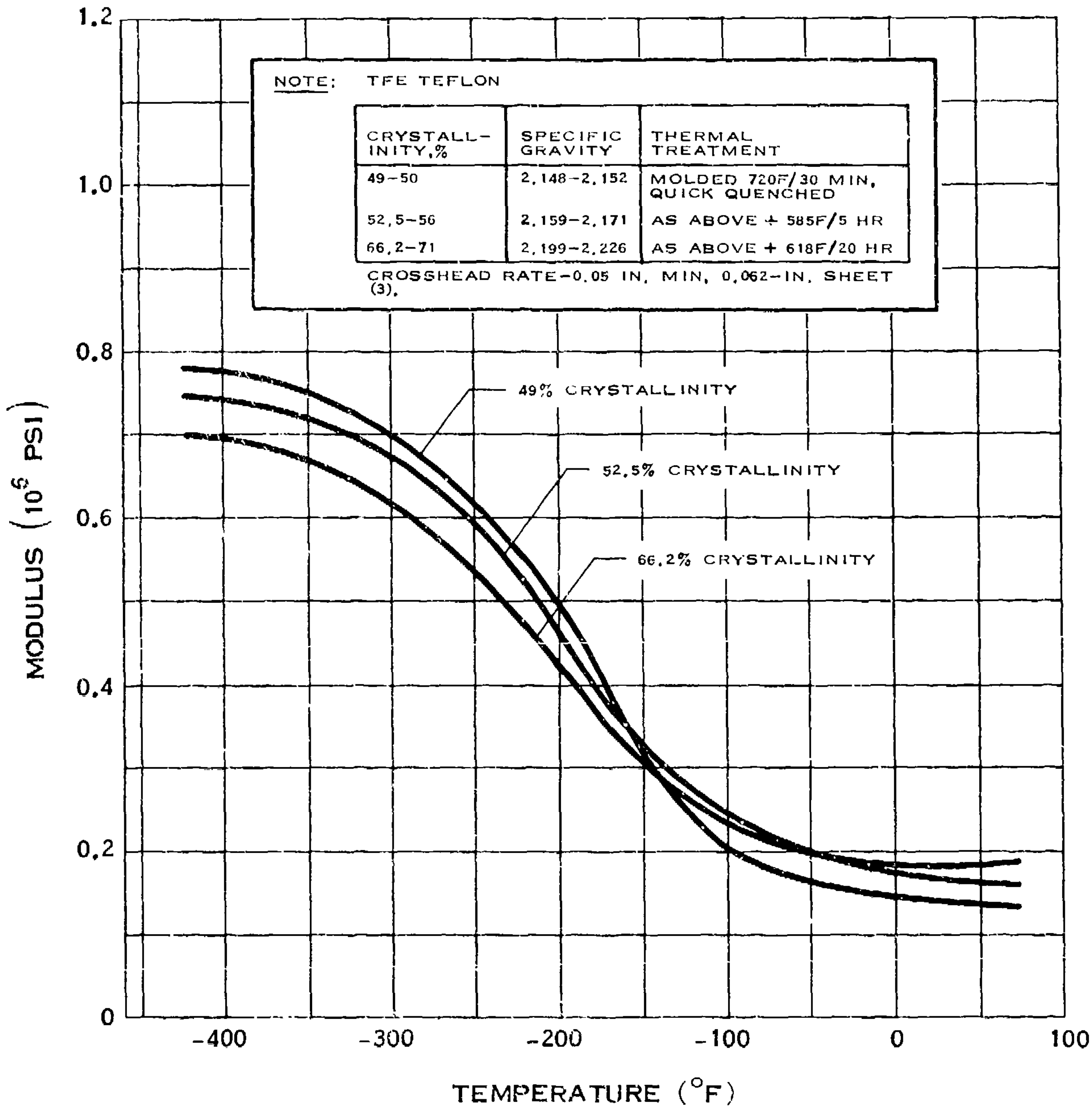
* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)



FLEXURAL STRENGTH OF TEFLON*

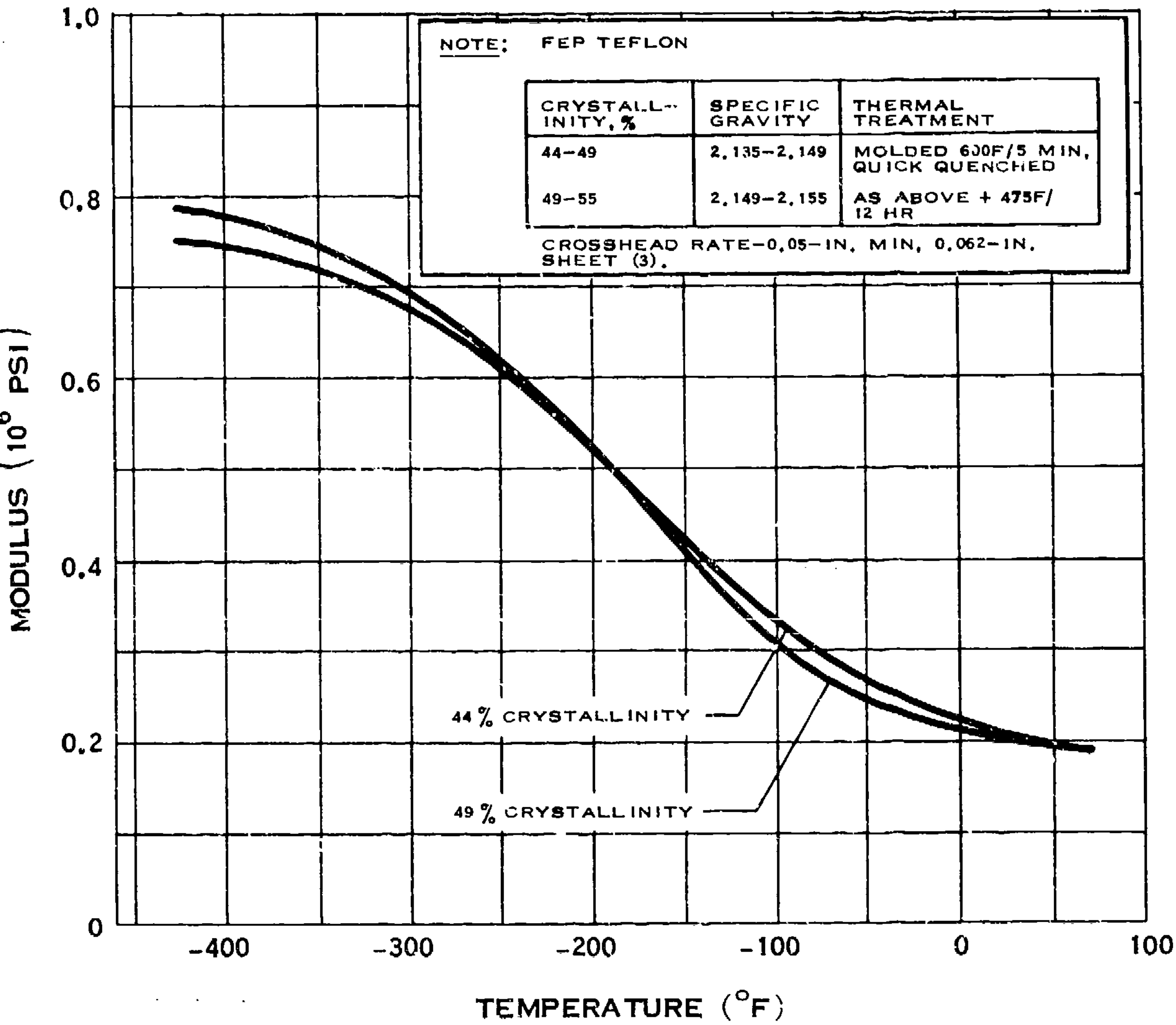
*T.M.
E. I. DUPONT DE NEMOURS AND CO.



FLEXURAL MODULUS OF TEFLON*

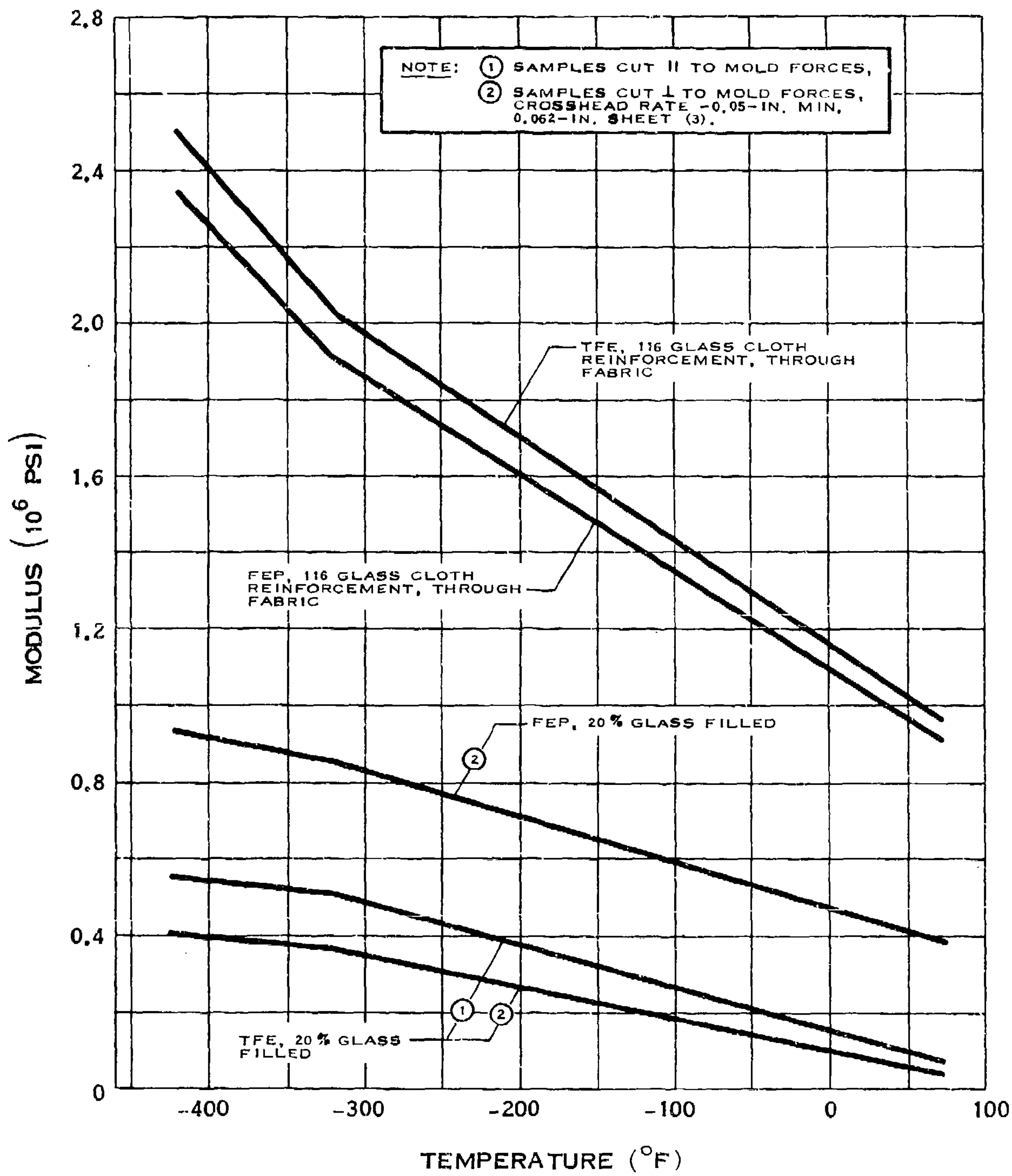
* T.M.
E. I. DUPONT DE NEMOURS AND CO.

(7-64)



FLEXURAL MODULUS OF TEFLON*

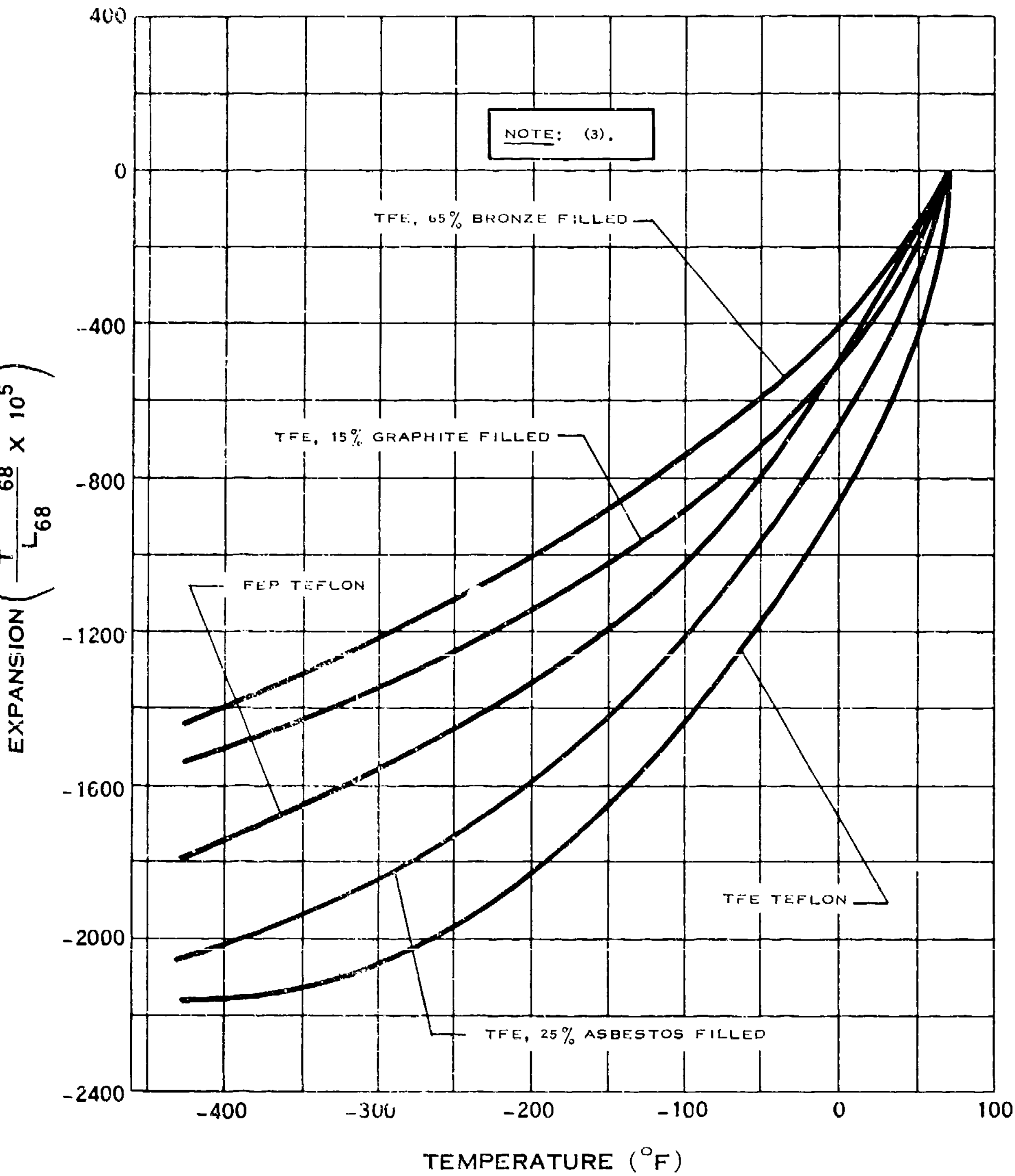
*T.M. E. I. DUPONT DE NEMOURS AND CO.



FLEXURAL MODULUS OF TEFLON*

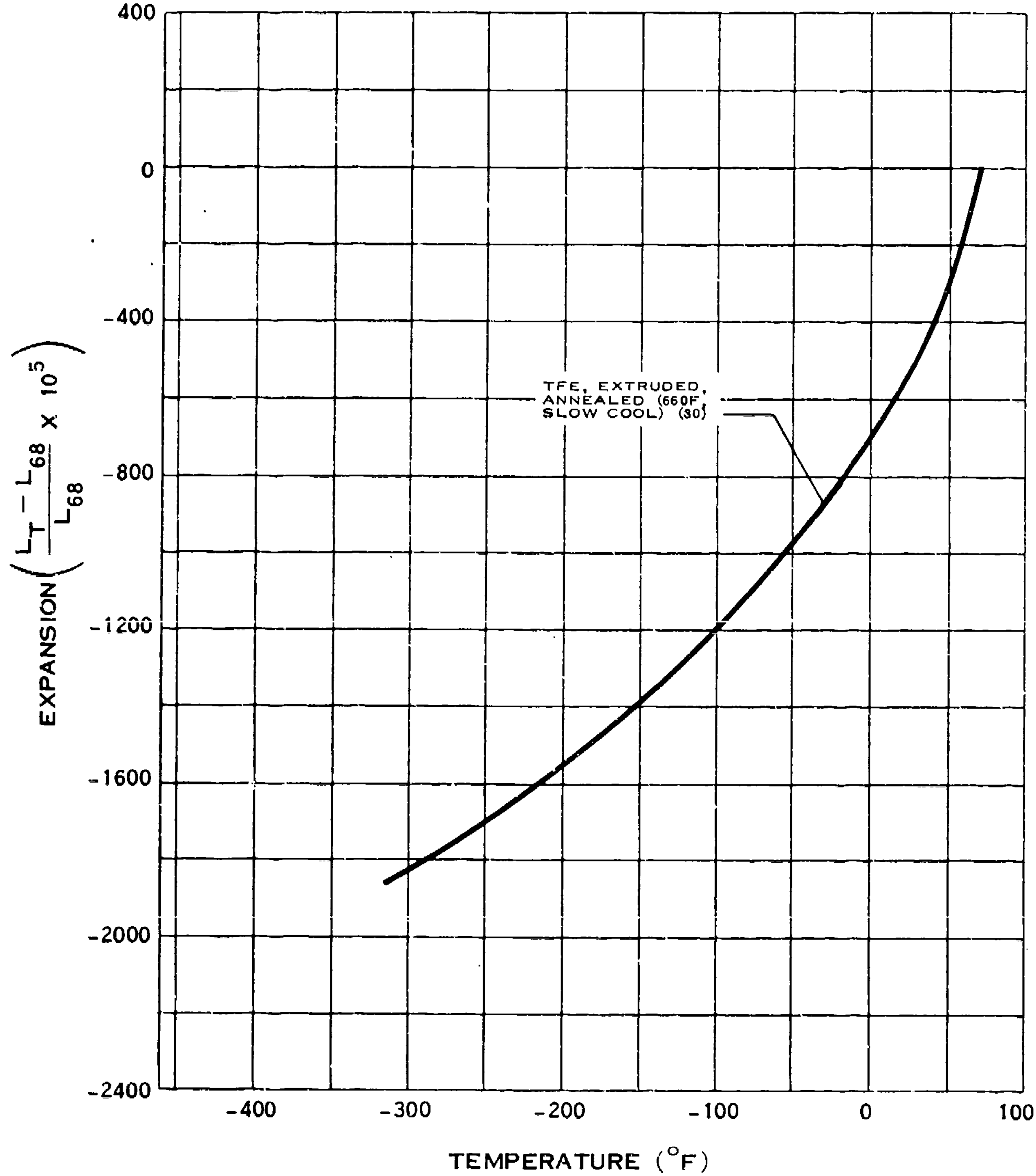
*T.M.
E. I. DUPONT DE NEMOURS AND CO.

(7-64)



THERMAL EXPANSION OF TEFLON*

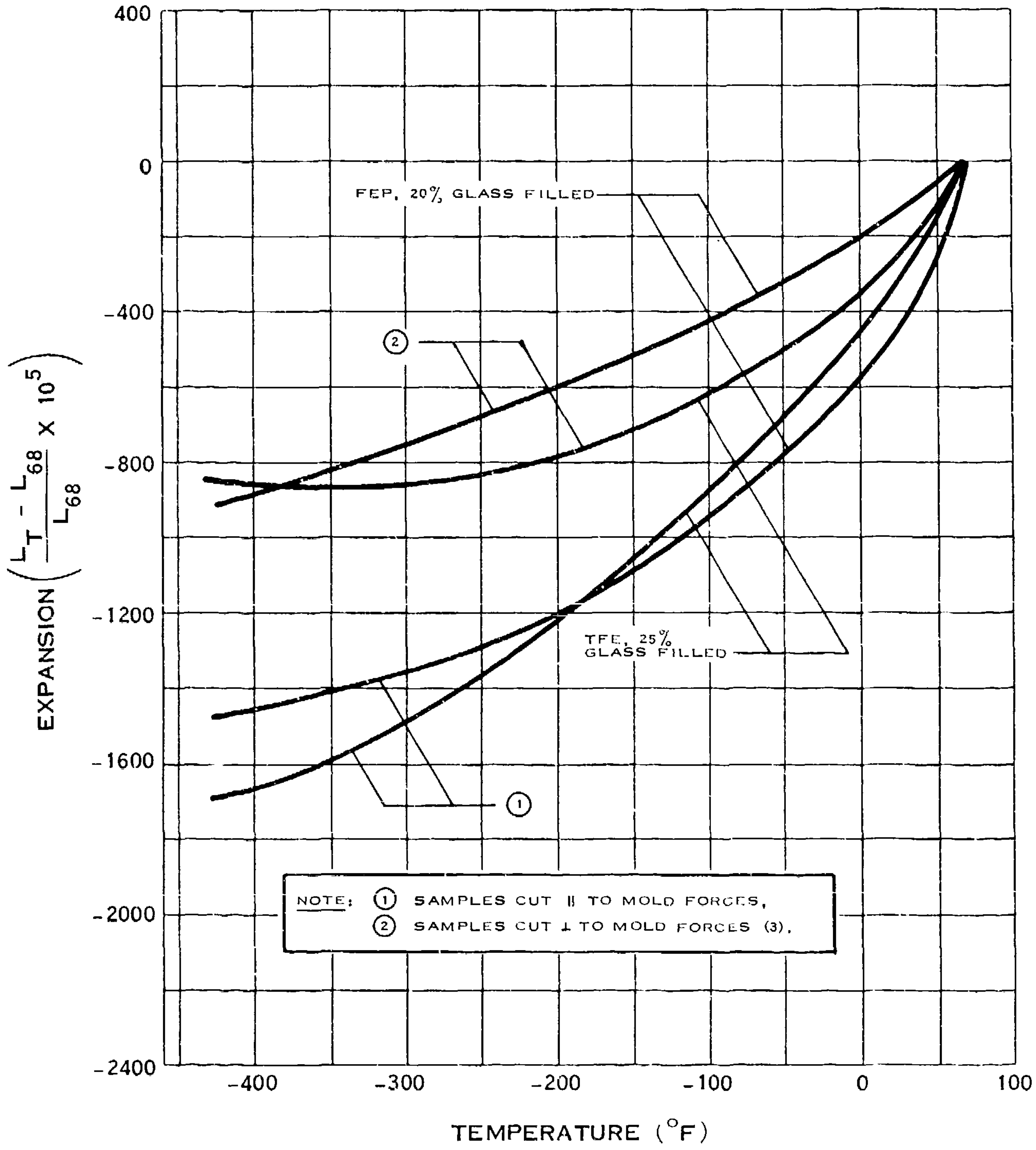
* T.M.
E. I. DUPONT DE NEMOURS AND CO.



THERMAL EXPANSION OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

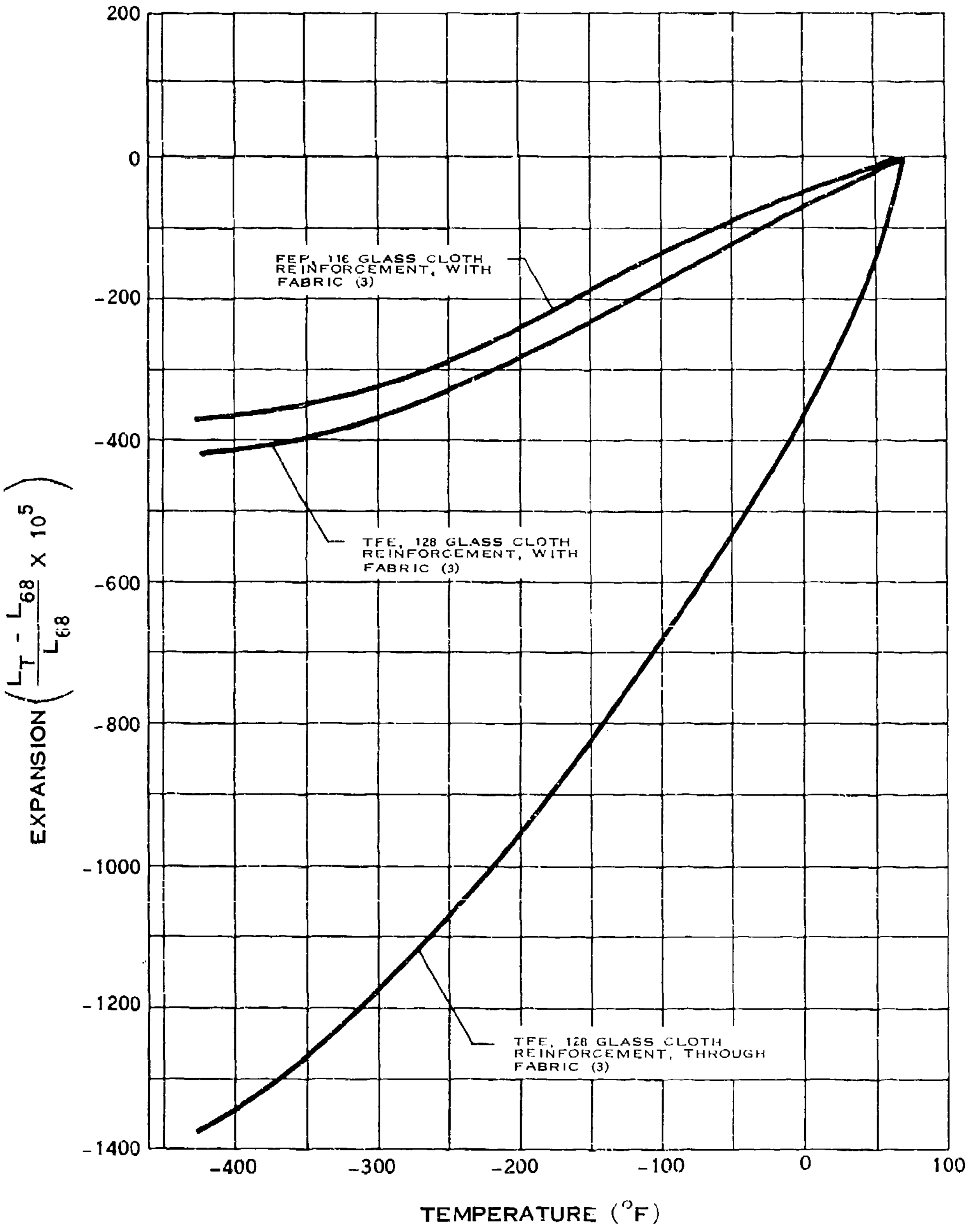
(7–64)



THERMAL EXPANSION OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

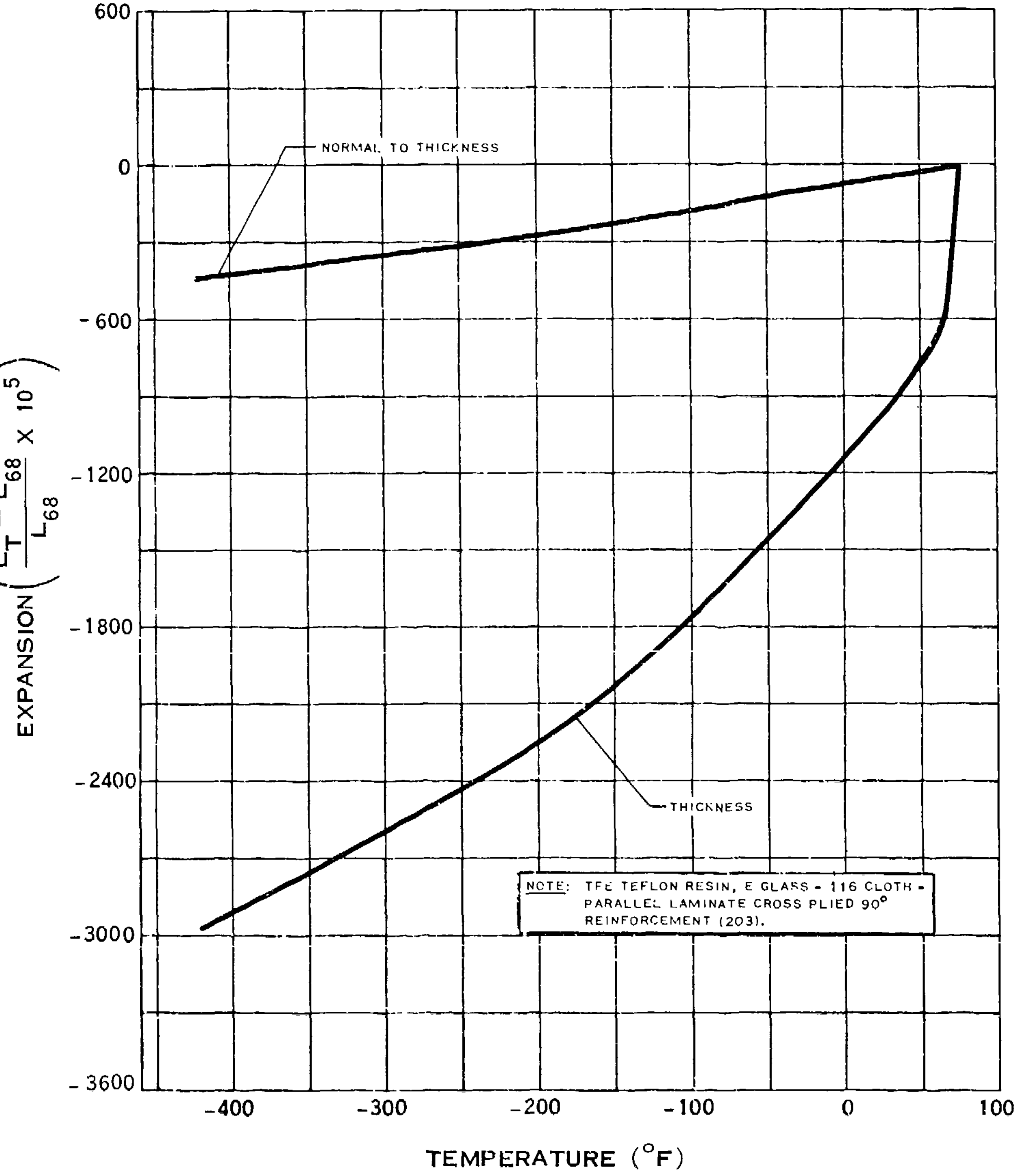
(7-64)



THERMAL EXPANSION OF TEFLON*

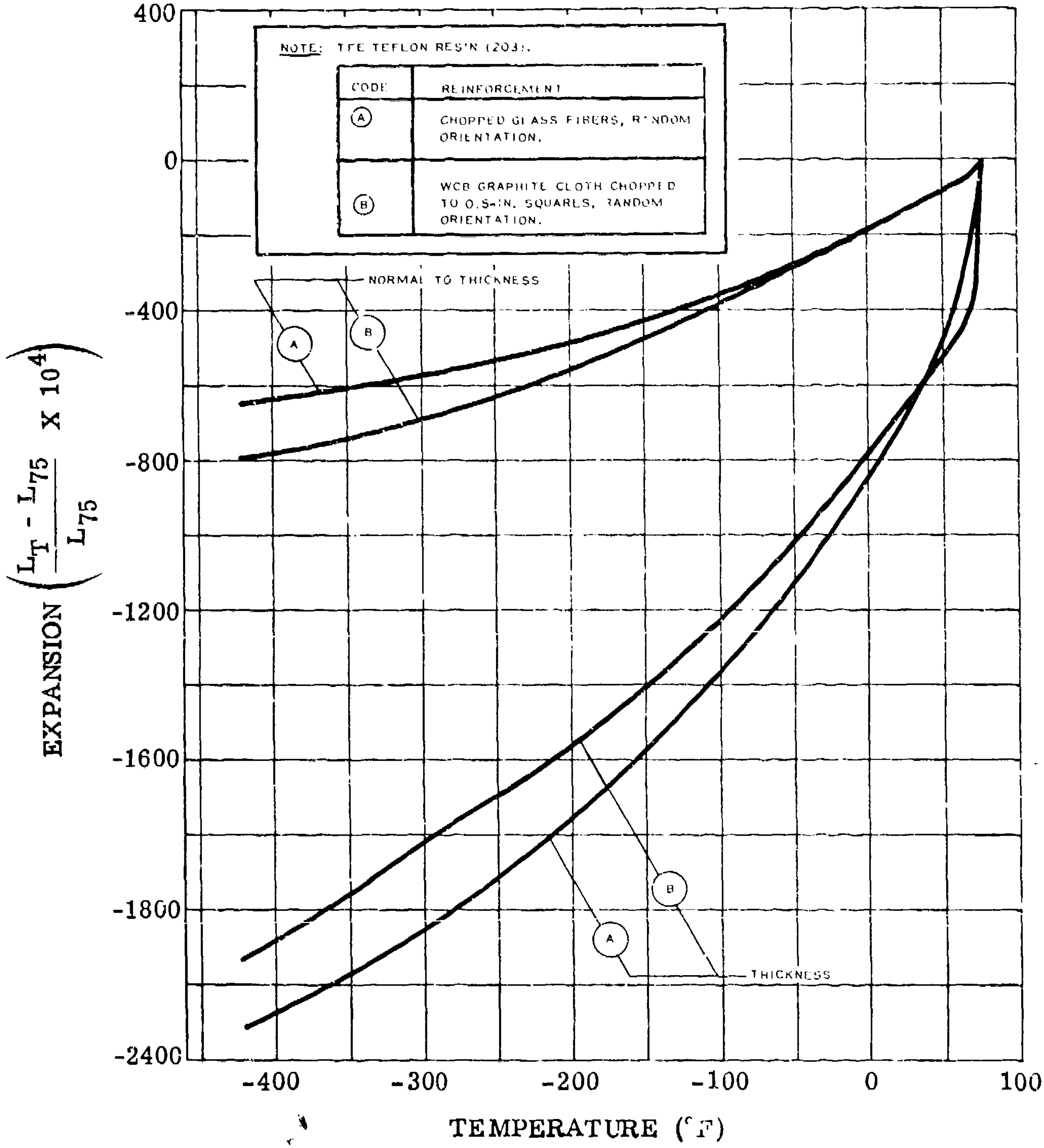
* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)



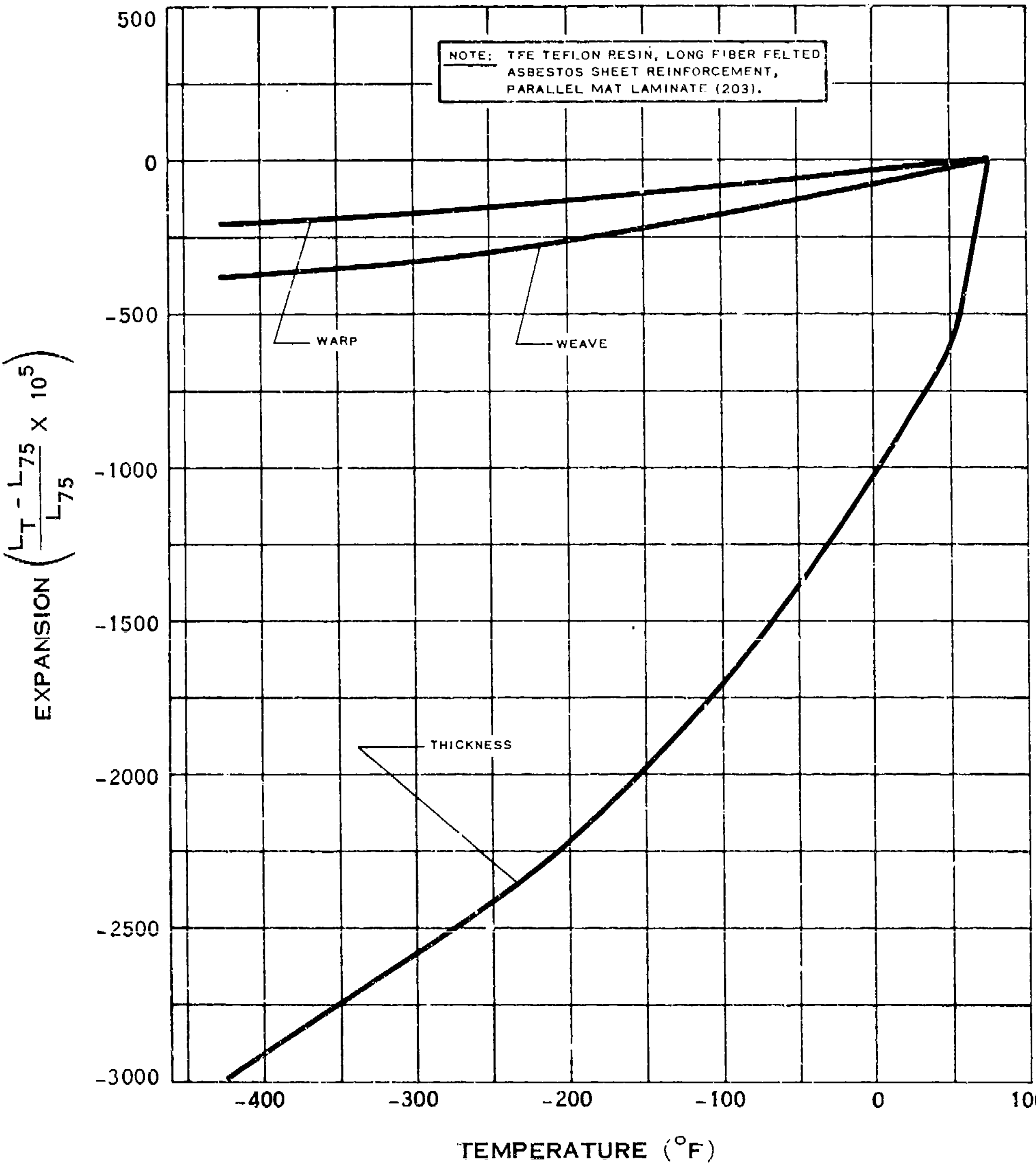
THERMAL EXPANSION OF TEFLON-FIBERGLAS LAMINATE

(6-68)



THERMAL EXPANSION OF REINFORCED MOLDED TEFLON

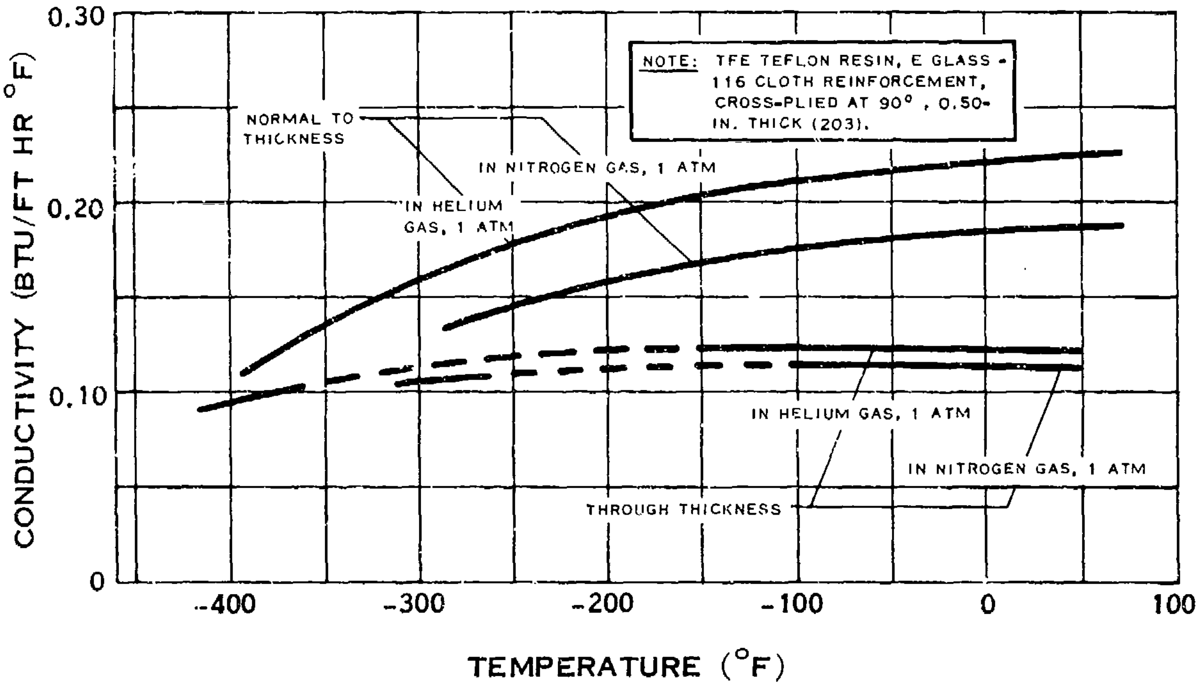
(6-68)



THERMAL EXPANSION OF TEFLON-ASBESTOS LAMINATE

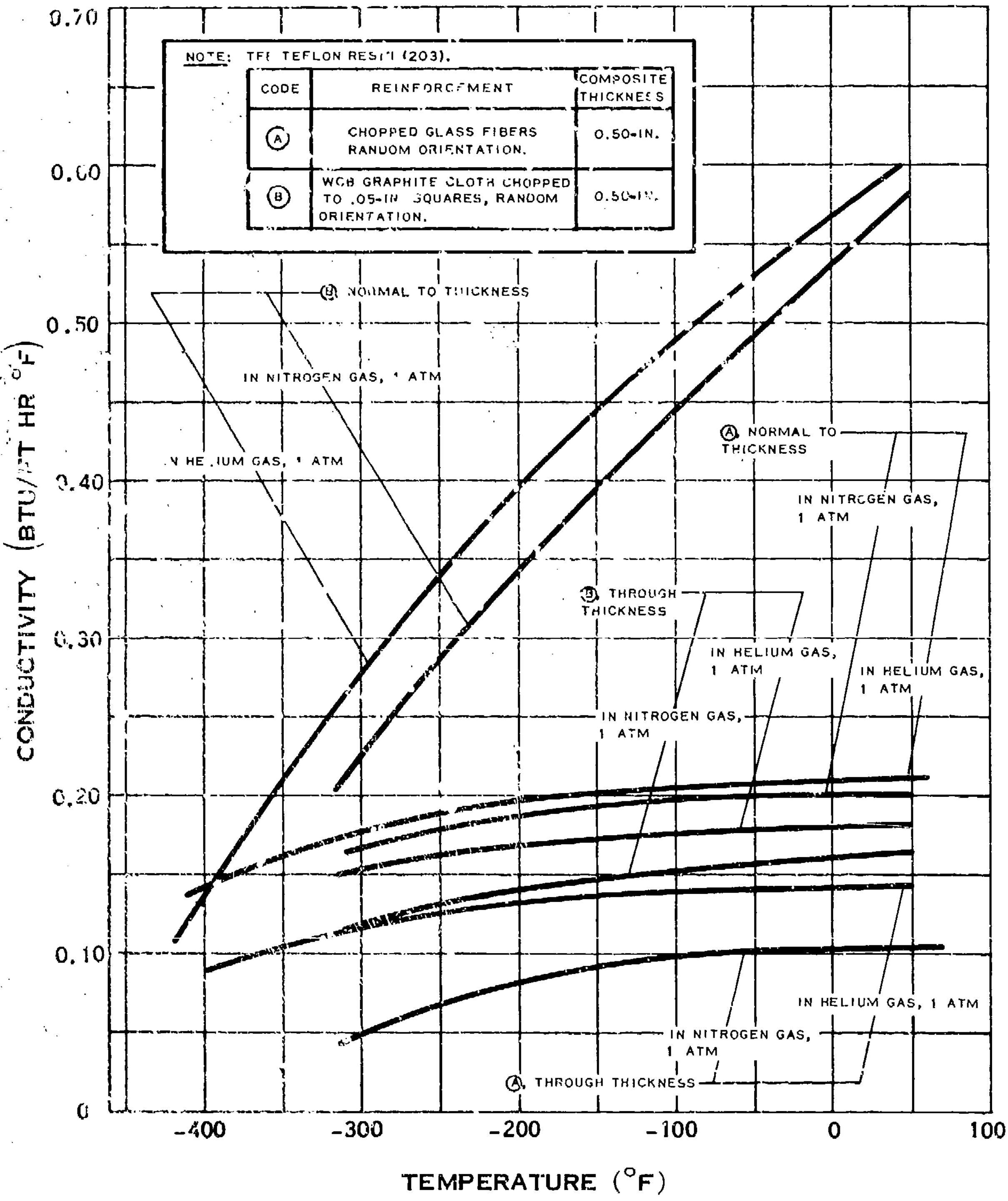
(6-68)

G.3.v



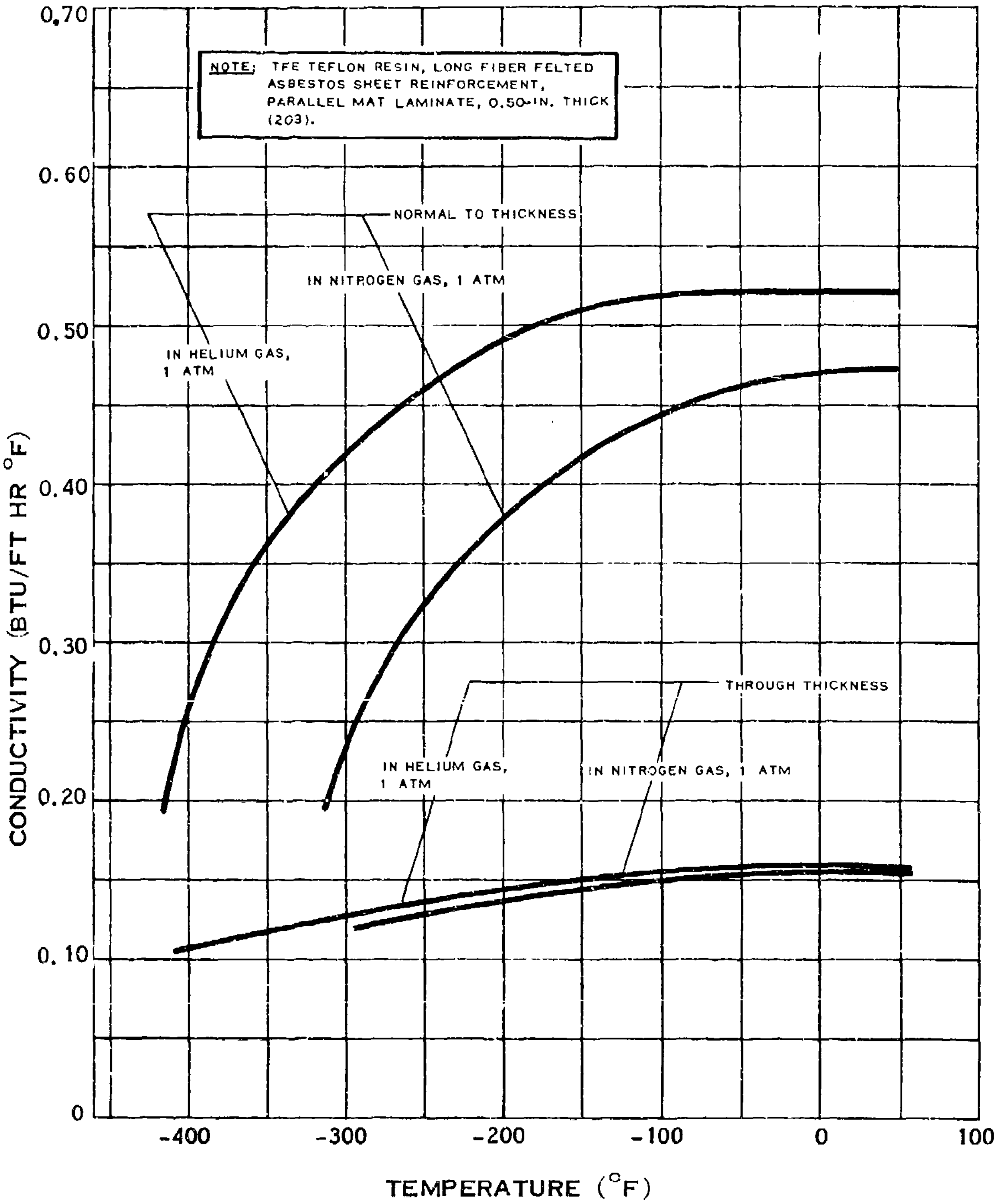
THERMAL CONDUCTIVITY OF TEFLON-FIBERGLAS LAMINATE

(6-68)



THERMAL CONDUCTIVITY OF REINFORCED MOLDED TEFLON

(6-68)



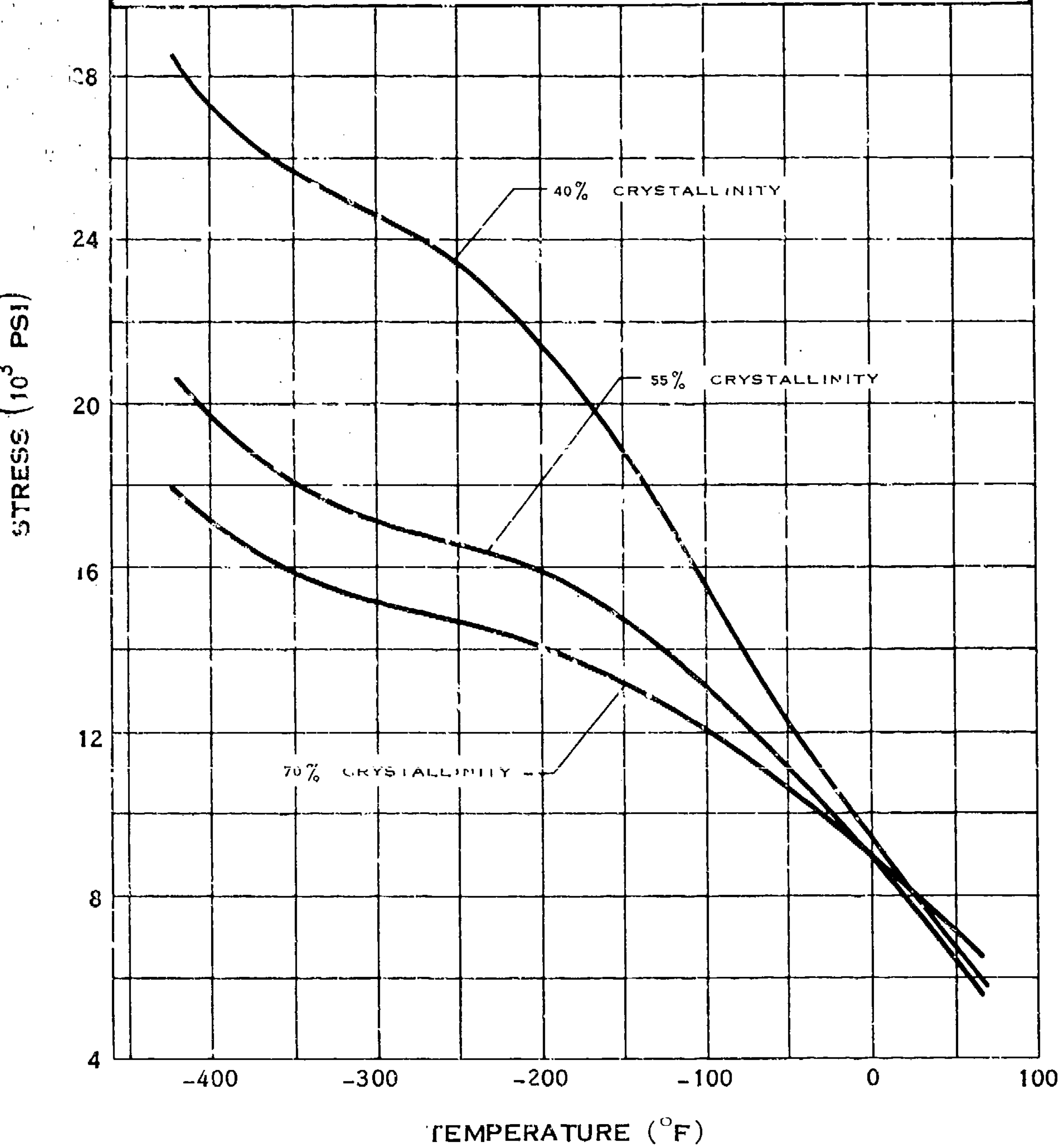
THERMAL CONDUCTIVITY OF TEFLON-ASBESTOS LAMINATE

(6-68)

NOTE:

CRYSTALL-INITY, %	SPECIFIC GRAVITY	THERMAL HISTORY
40	2.10	MOLDED 525F/5 MIN, QUENCHED
55	2.12	AS-RECEIVED +300F/4 HR, SLOW COOL
70	2.14	AS-RECEIVED +395F/24 HR, SLOW COOL

CROSSHEAD RATE: 1-IN./MIN-70F, 0.1-IN./MIN-LOWER TEMPERATURES
0.062-IN. SHEET (3).

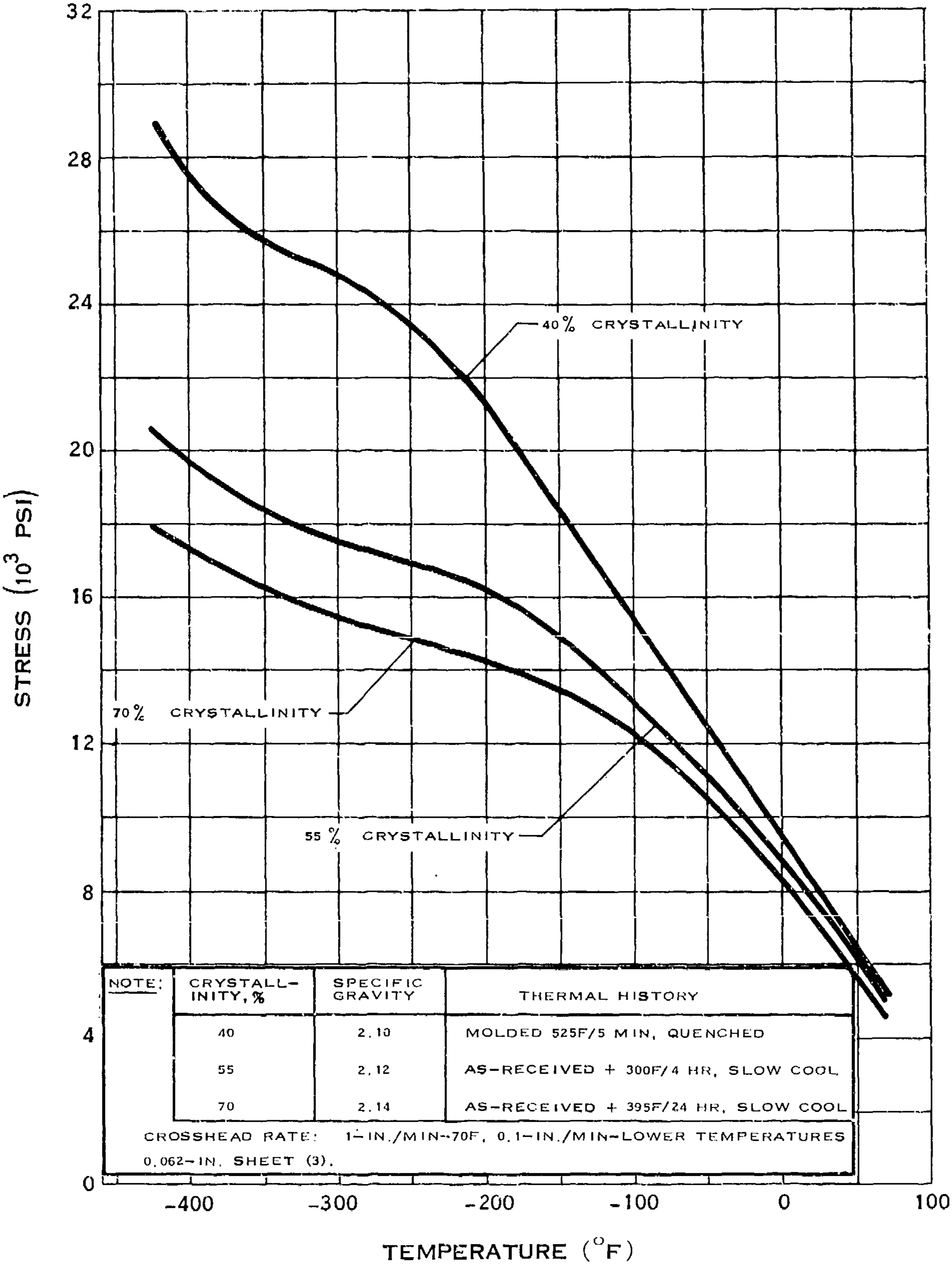


YIELD STRENGTH OF KEL-F*

* T.M.
MINNESOTA MINING AND MFG. CO.

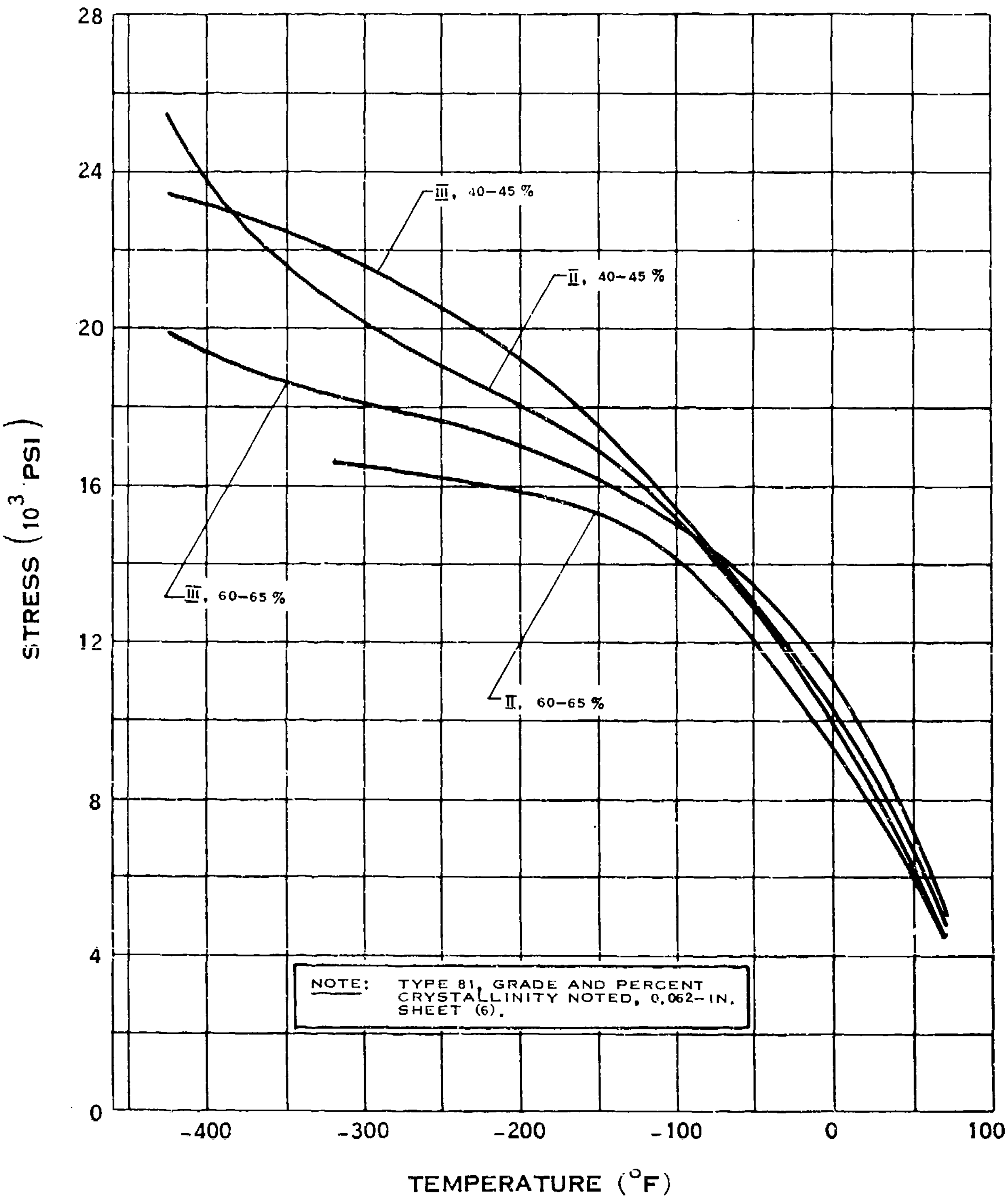
(7-64)

G.4.b



TENSILE STRENGTH OF KEL-F*

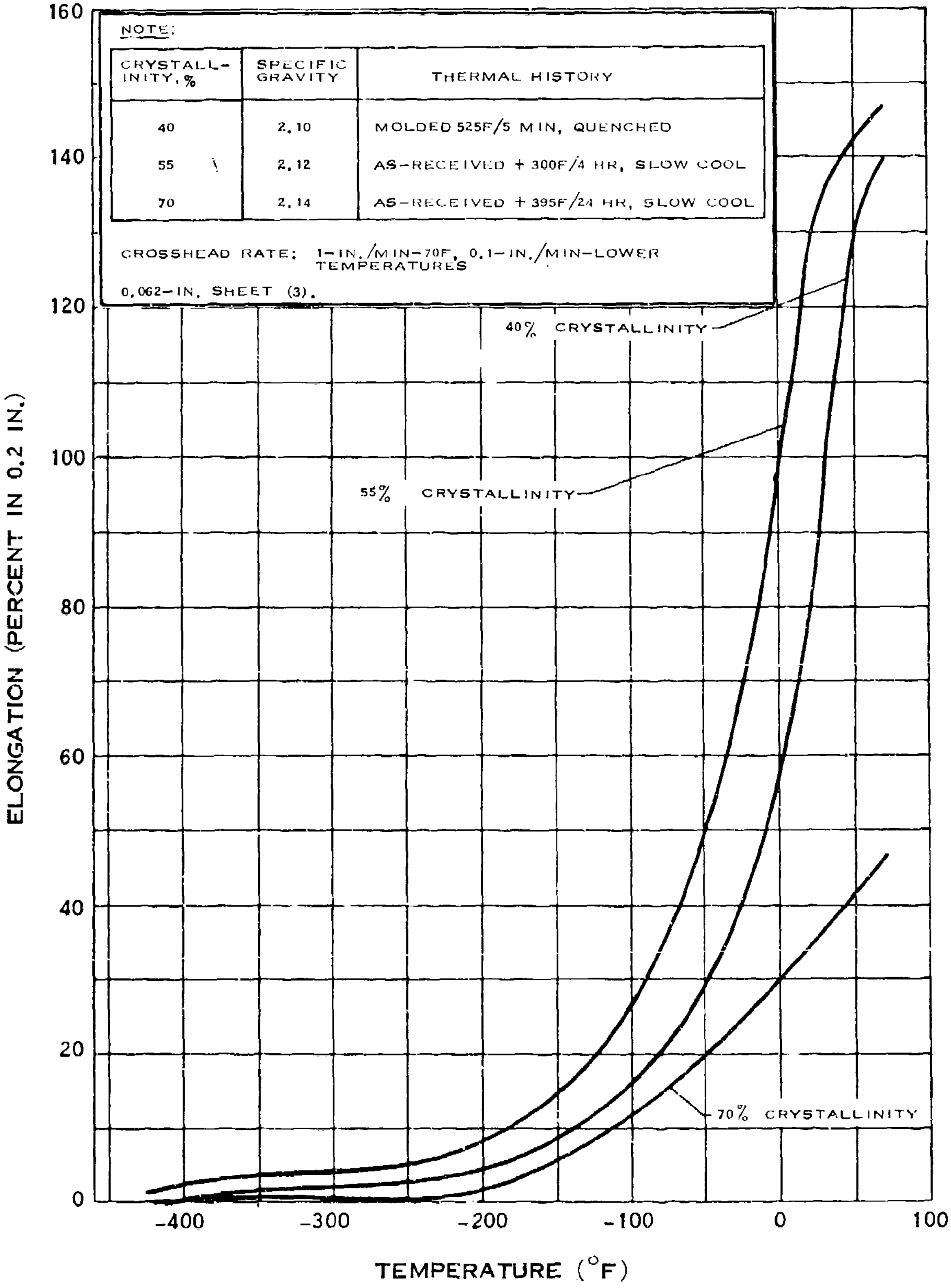
* T.M. MINNESOTA MINING AND MFG. CO.



TENSILE STRENGTH OF KEL-F*

*T.M. MINNESOTA MINING AND MFG. CO.

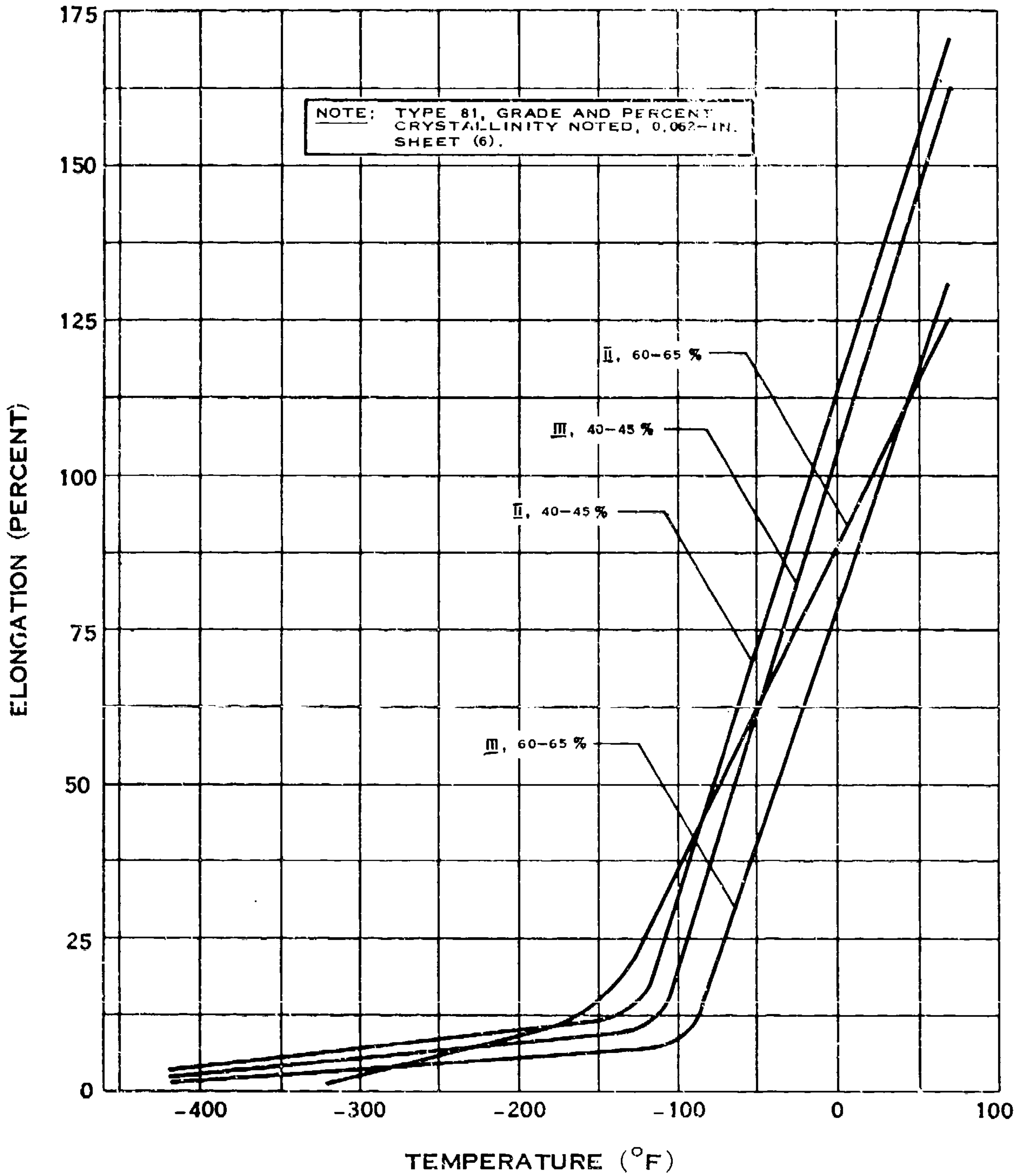
(7-64)



ELONGATION OF KEL-F*

* T.M. MINNESOTA MINING AND MFG. CO.

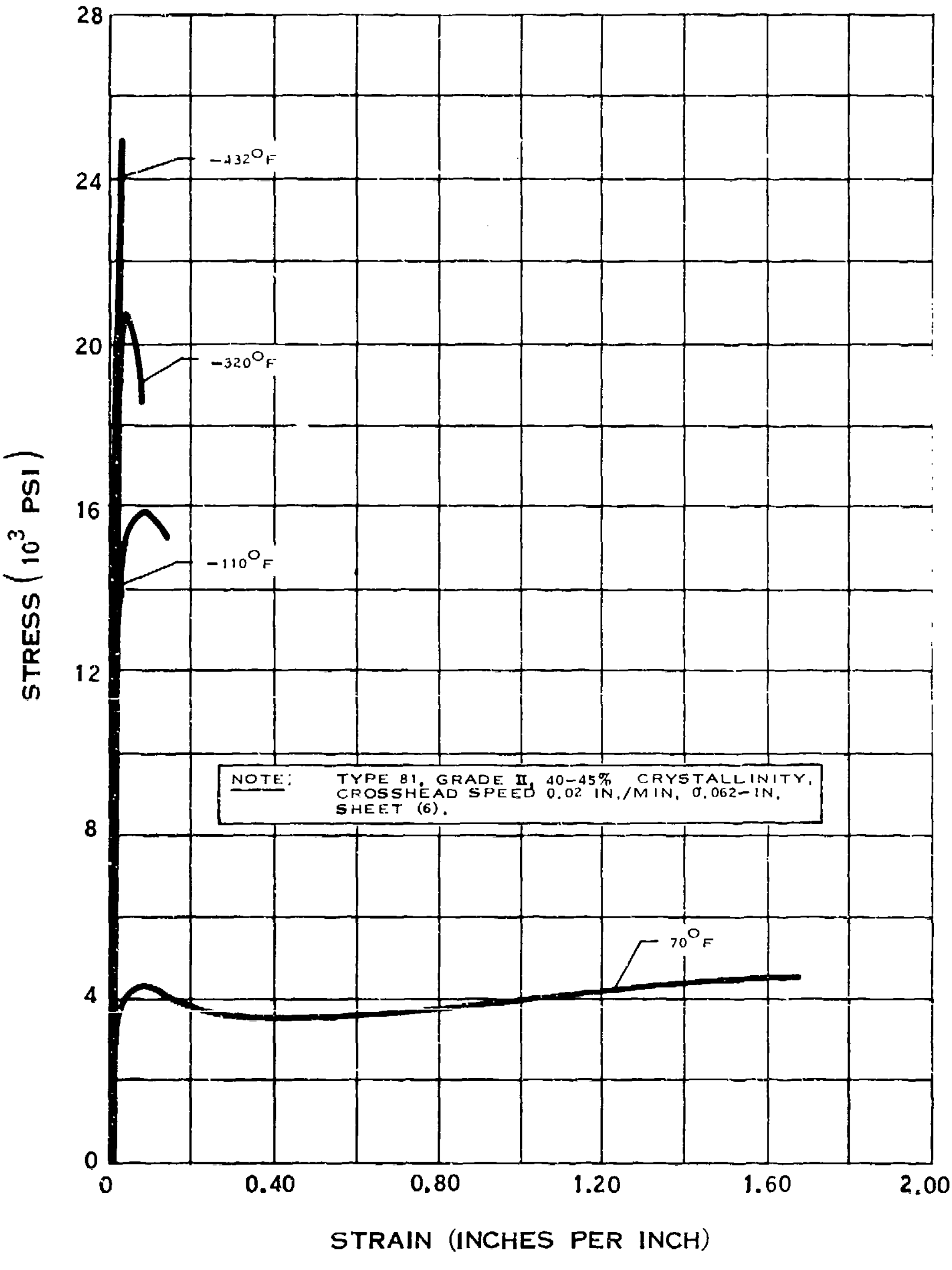
(1-65)



ELONGATION OF KEL-F*

* T.M.
MINNESOTA MINING AND MFG. CO.

(7-64)

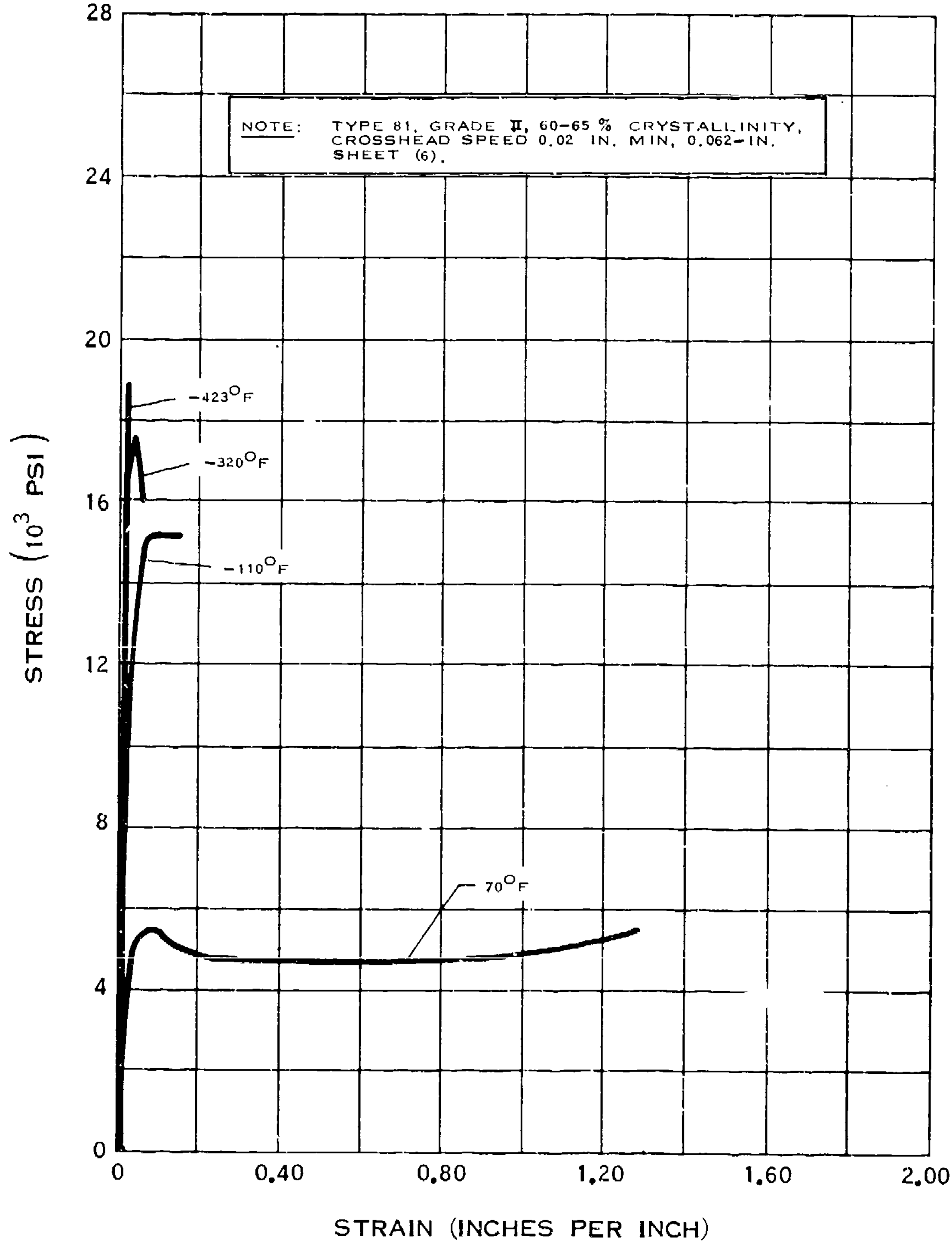


STRESS-STRAIN DIAGRAM FOR KEL-F*

* T.M.
MINNESOTA MINING AND MFG. CO.

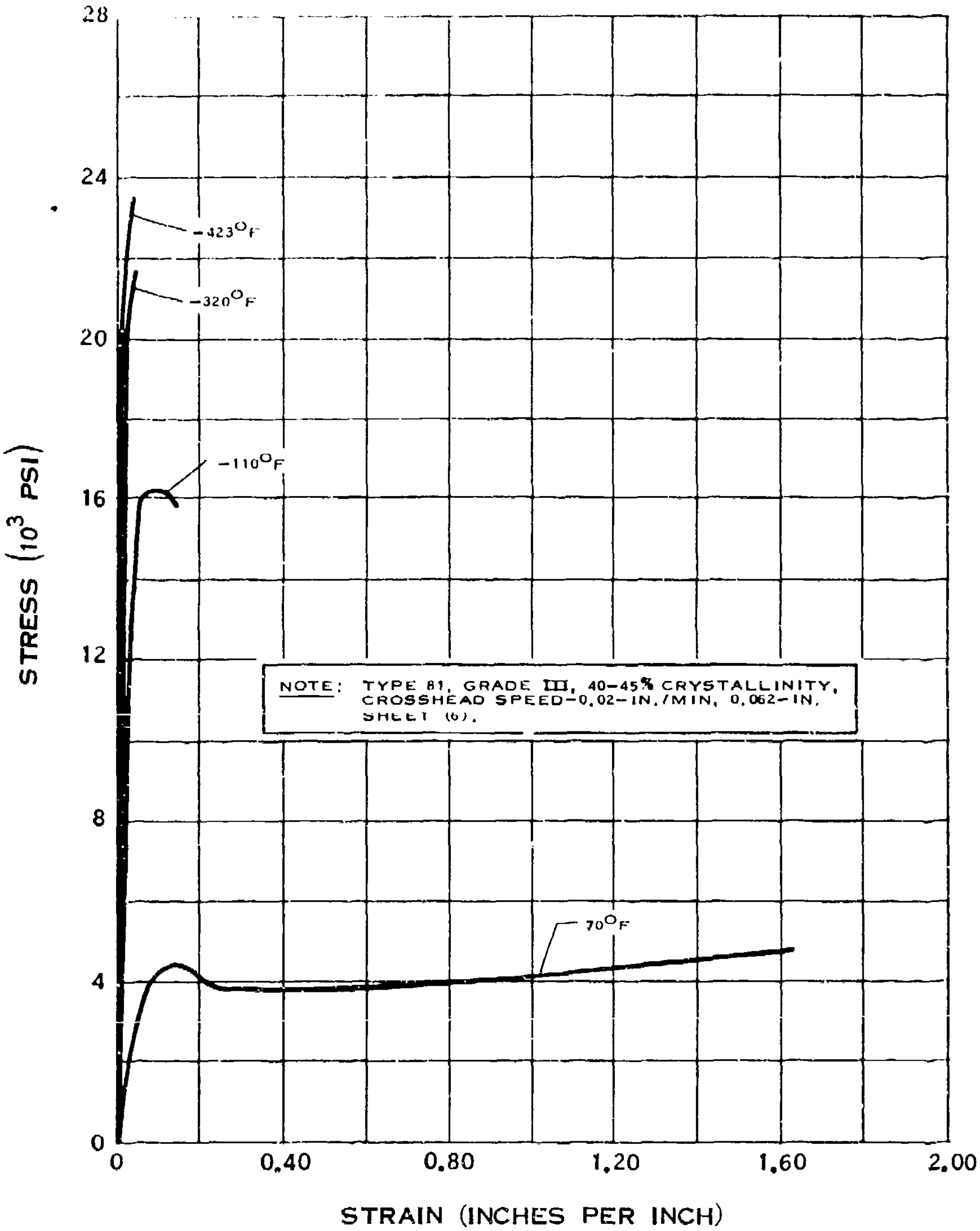
(1-65)

G.4.h-1



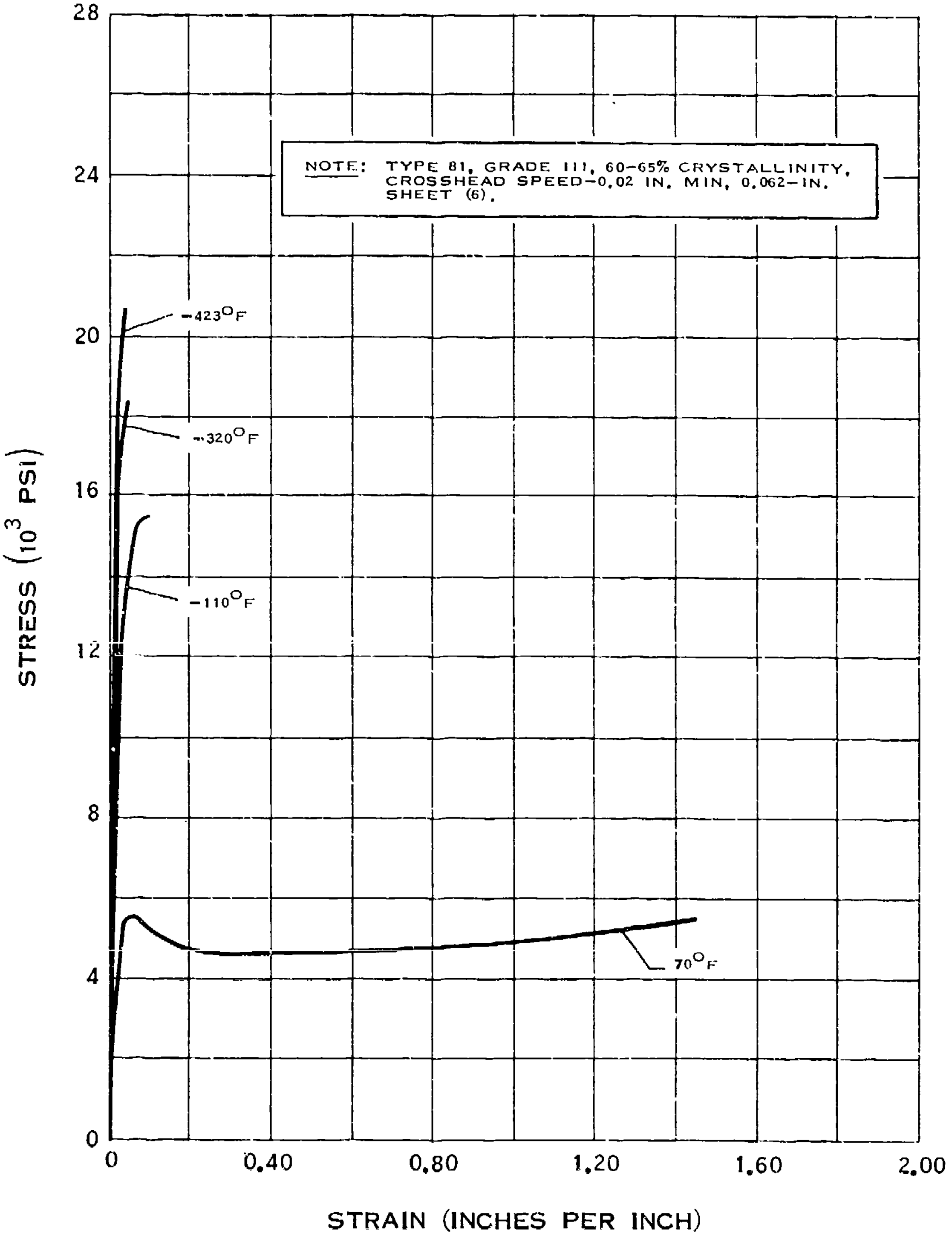
STRESS-STRAIN DIAGRAM FOR KEL-F*

* T.M.
MINNESOTA MINING AND MFG. CO.



STRESS-STRAIN DIAGRAM FOR KEL-F*

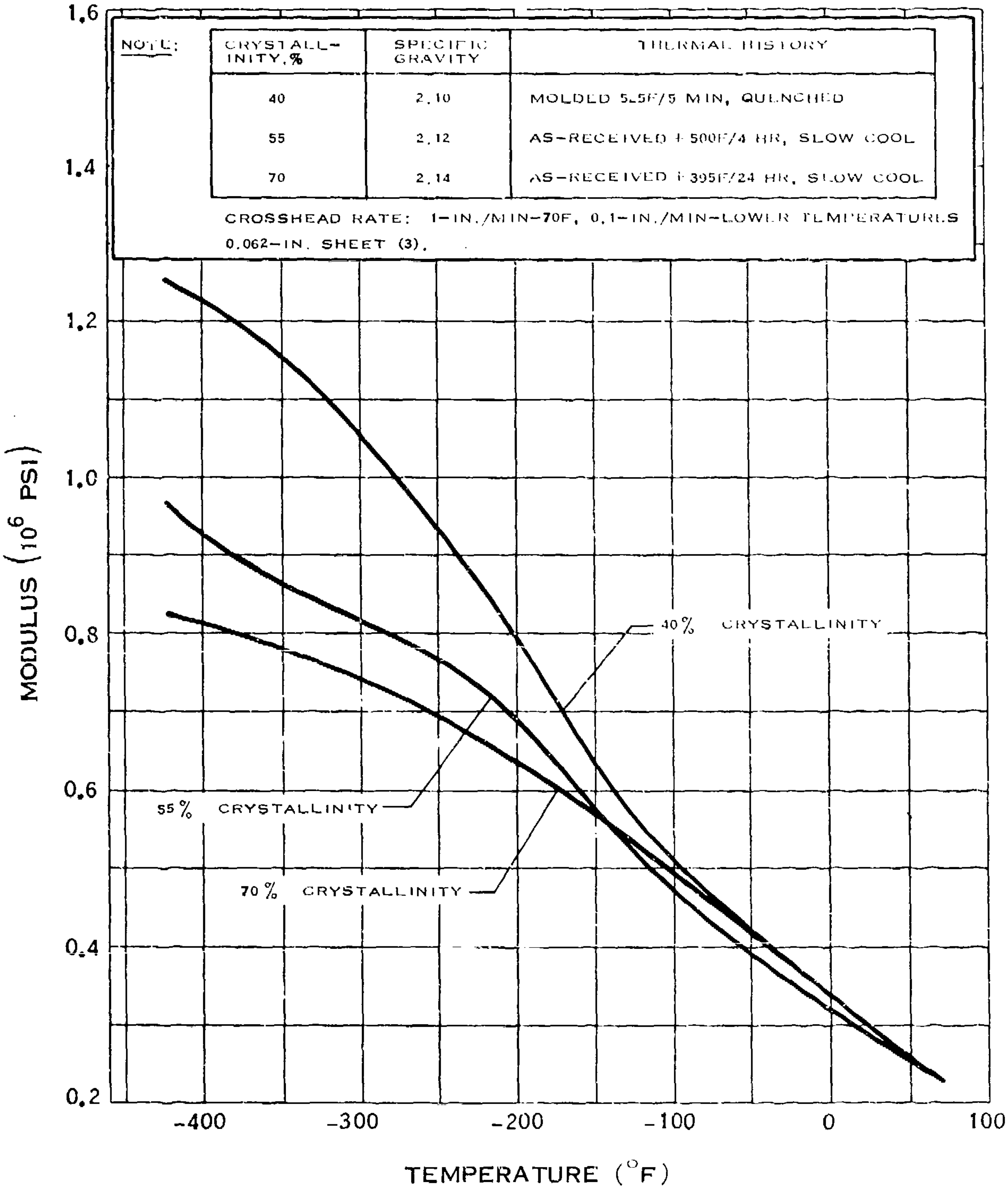
* T.M. MINNESOTA MINING AND MFG. CO.



STRESS-STRAIN DIAGRAM FOR KEL-F*

* T.M.
MINNESOTA MINING AND MFG. CO.

(7-64)



NOTE:

CRYSTALL-INITY, %	SPECIFIC GRAVITY	THERMAL HISTORY
40	2.10	MOLDED 525F/5 MIN, QUENCHED
55	2.12	AS-RECEIVED + 500F/4 HR, SLOW COOL
70	2.14	AS-RECEIVED + 395F/24 HR, SLOW COOL

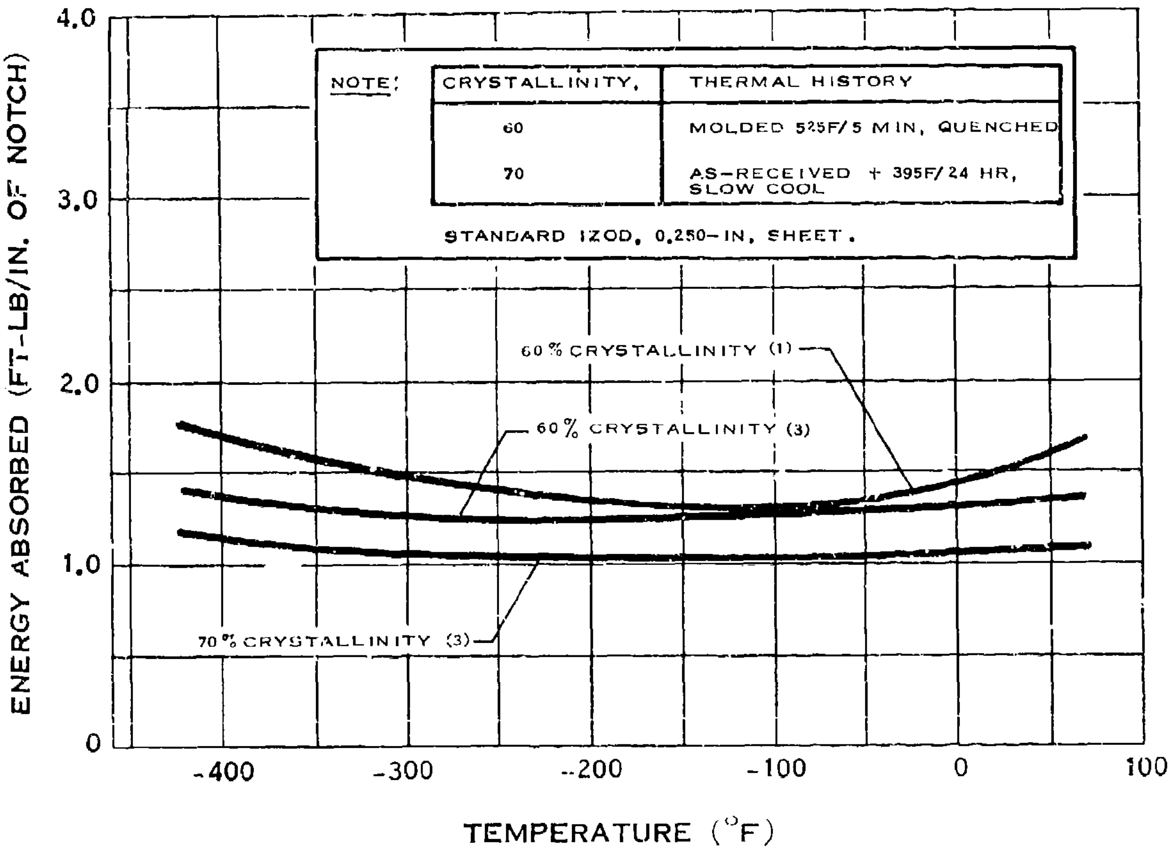
CROSSHEAD RATE: 1-IN./MIN-70F, 0.1-IN./MIN-LOWER TEMPERATURES
0.062-IN. SHEET (3).

MODULUS OF ELASTICITY OF KEL-F*

*T.M. MINNESOTA MINING AND MFG. CO.

(7-64)

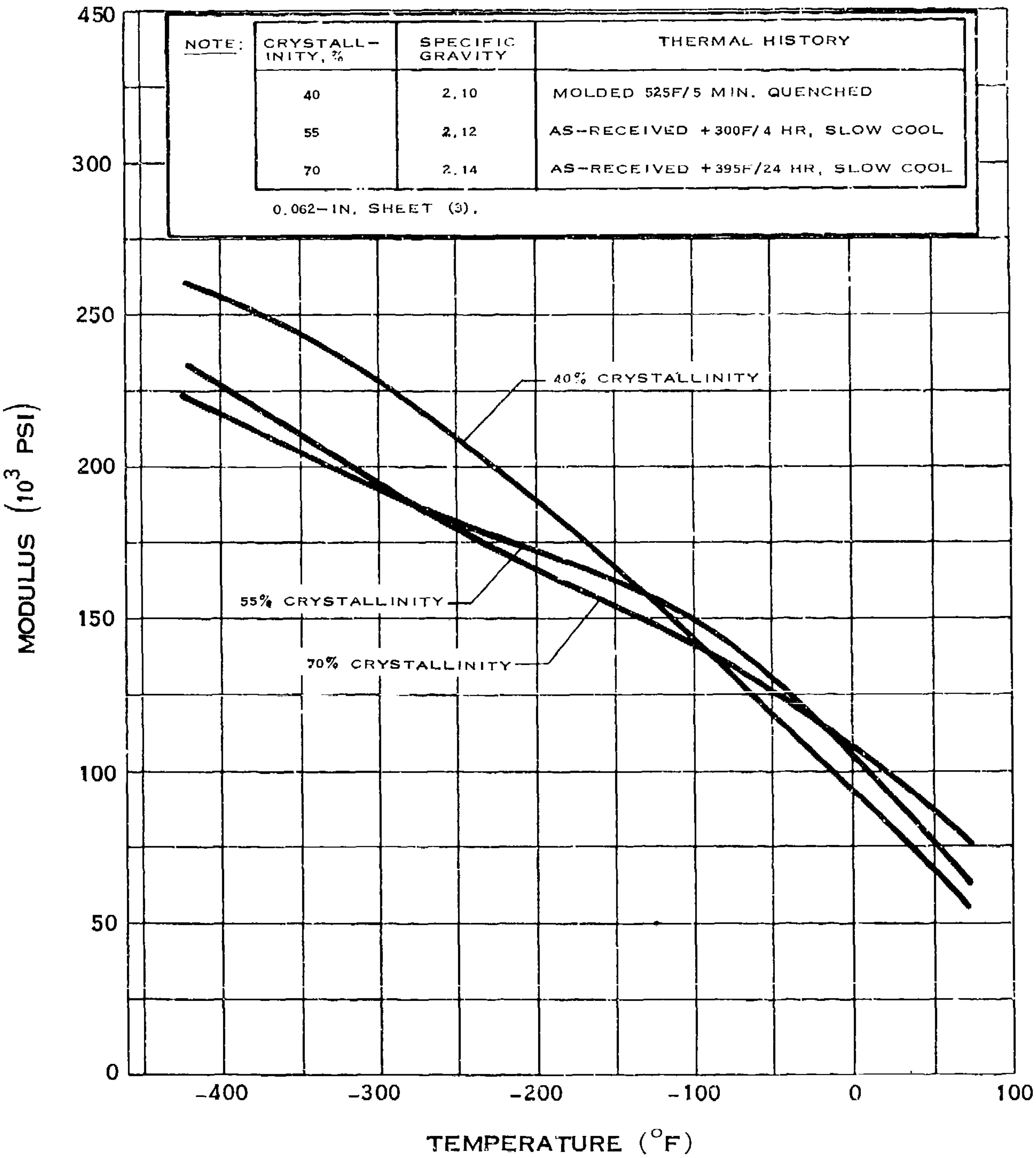
G.4.j



IMPACT STRENGTH OF KEL-F*

*T.M. MINNESOTA MINING AND MFG, CO.

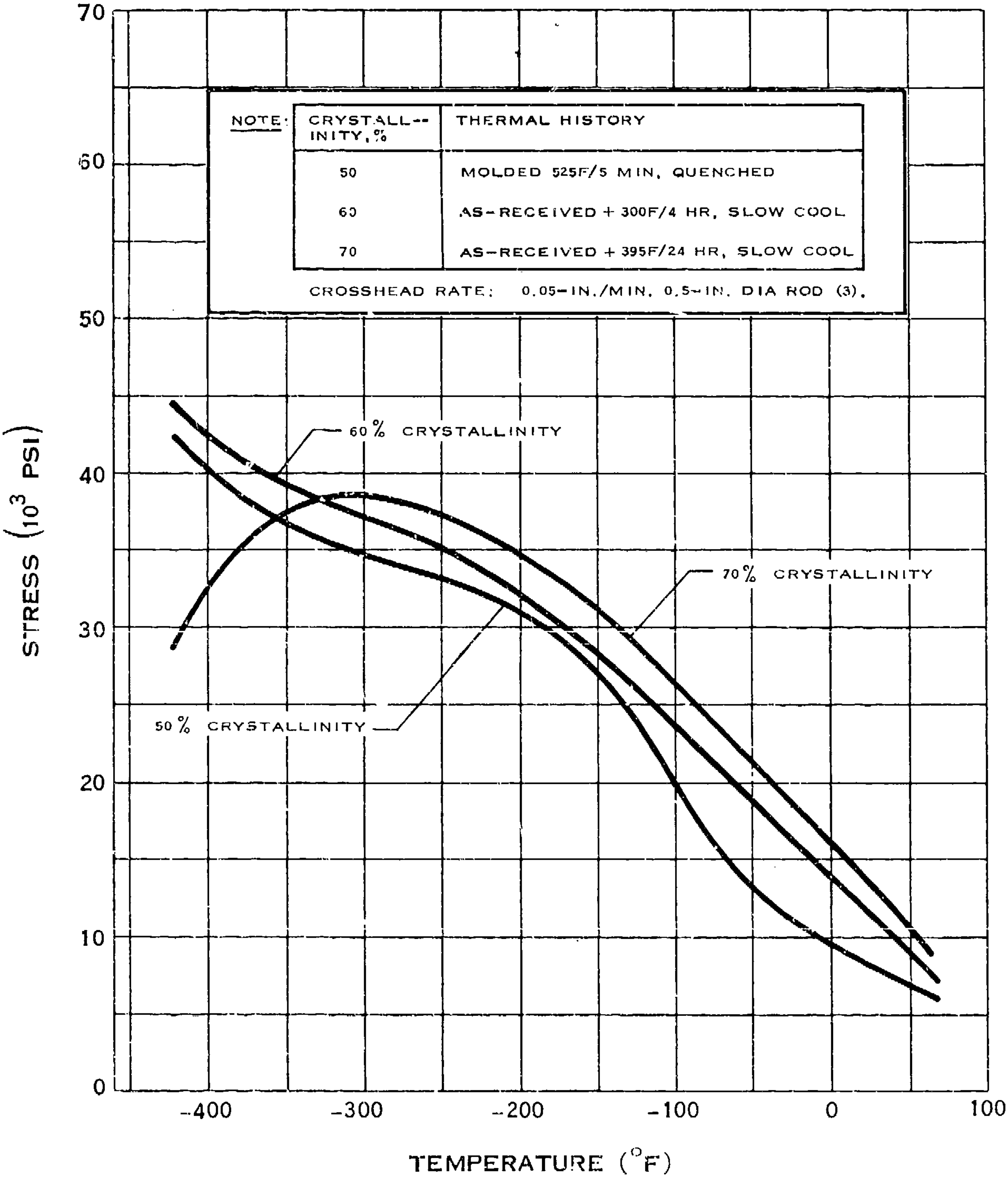
(7-65)



MODULUS OF RIGIDITY OF KEL-F*

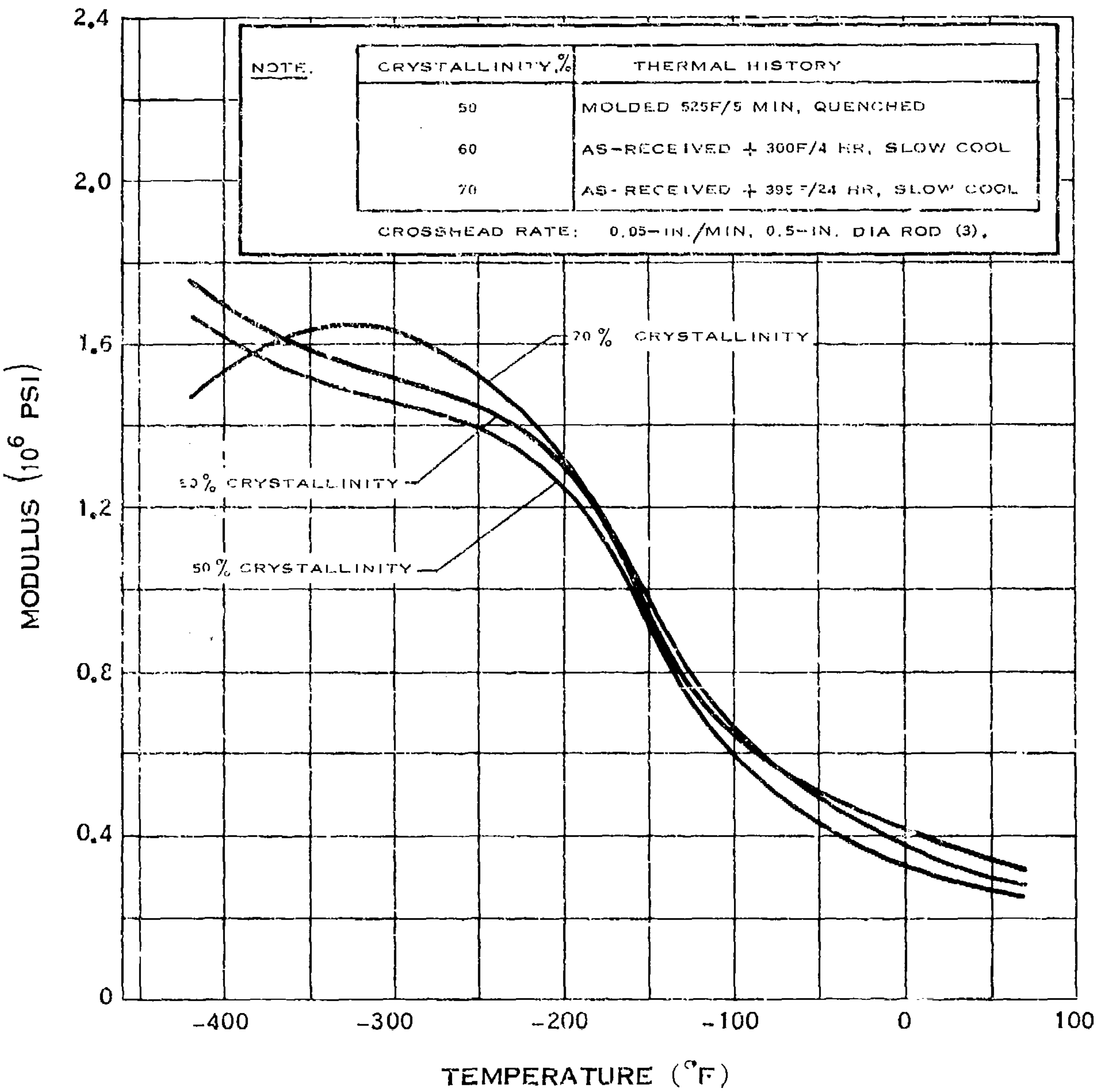
* T.M.
MINNESOTA MINING AND MFG. CO.

(7-6?)



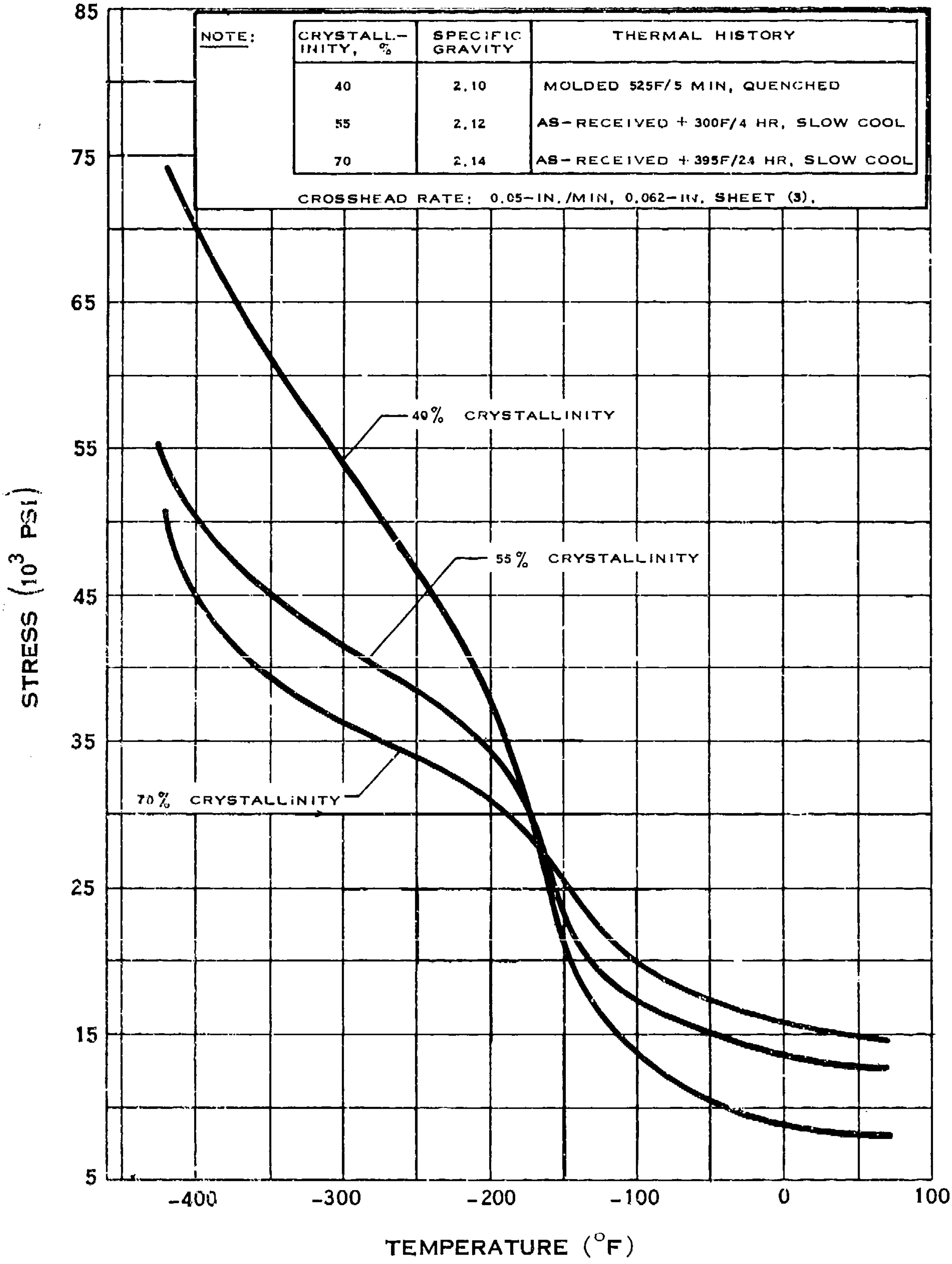
COMPRESSIVE STRENGTH OF KEL-F*

*T.M.
MINNESOTA MINING AND MFG. CO.



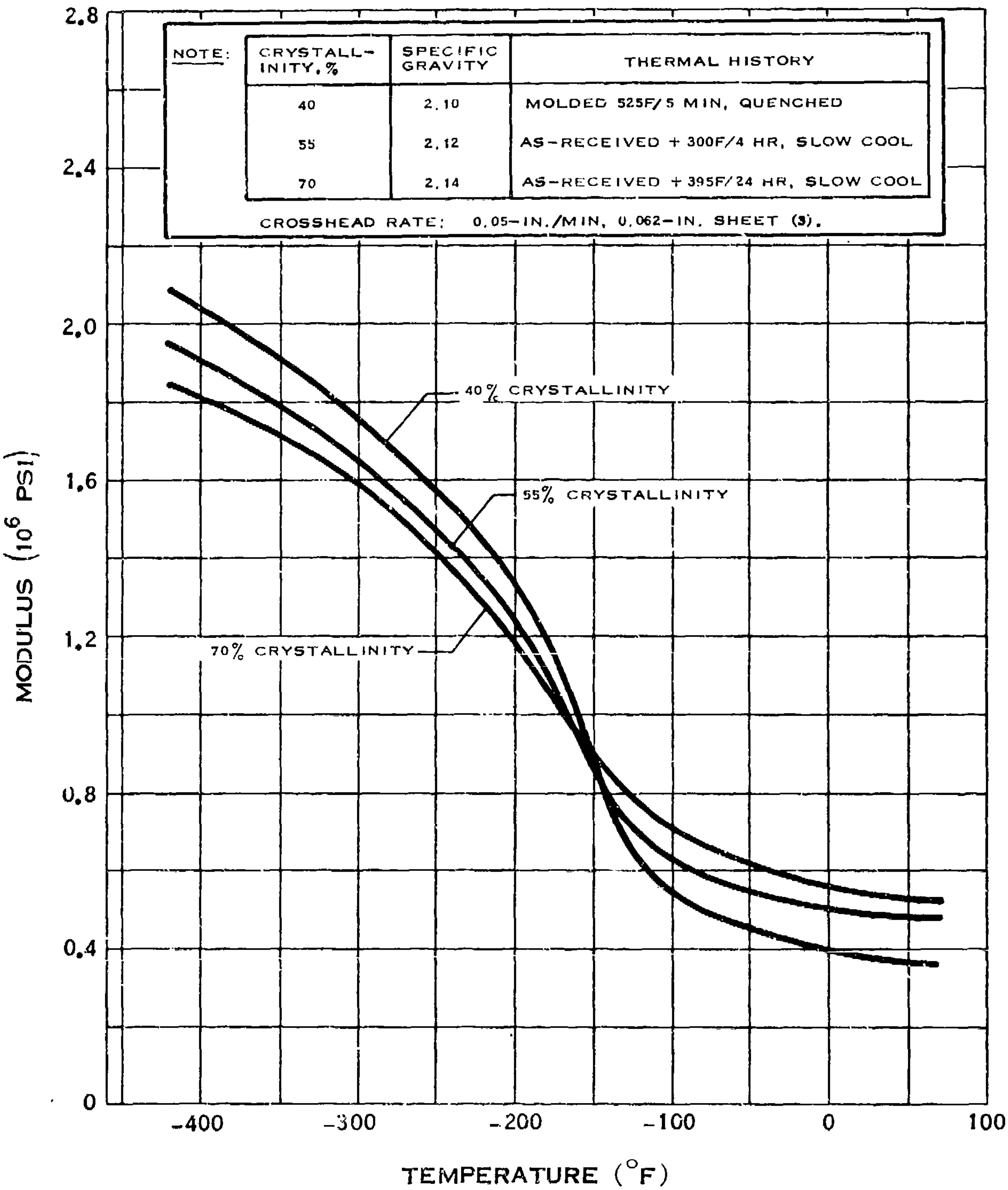
COMPRESSIVE MODULUS OF KEL-F*

*T.M. MINNESOTA MINING AND MFG, CO.



FLEXURAL STRENGTH OF KEL-F*

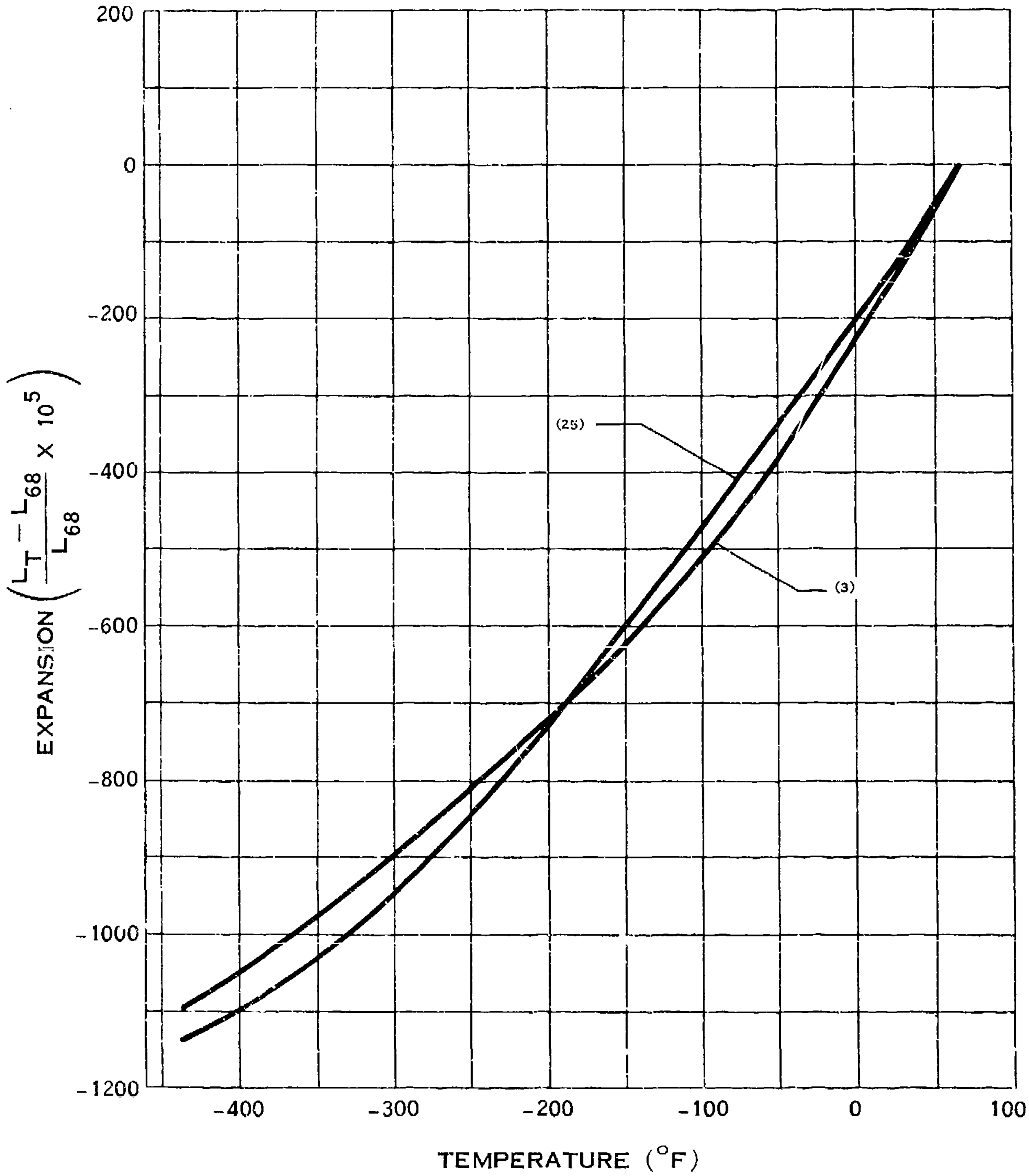
* T.M.
MINNESOTA MINING AND MFG. CO.



FLEXURAL MODULUS OF KEL-F*

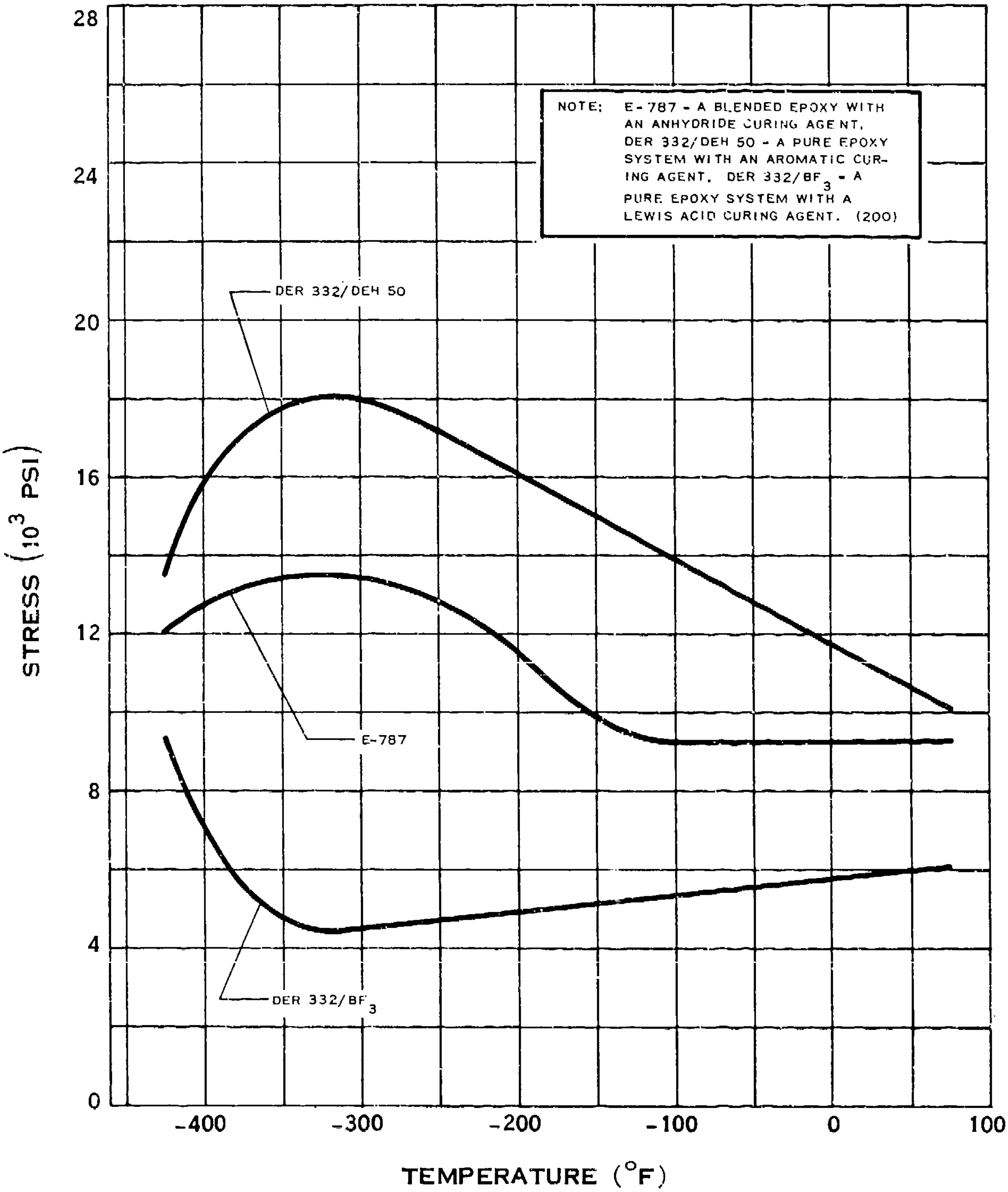
* T.M.
MINNESOTA MINING AND MFG. CO.

(7-64)



THERMAL EXPANSION OF KEL-F*

* T.M.
MINNESOTA MINING AND MFG. CO.



TENSILE STRENGTH OF CAST EPOXY RESIN

(6-68)

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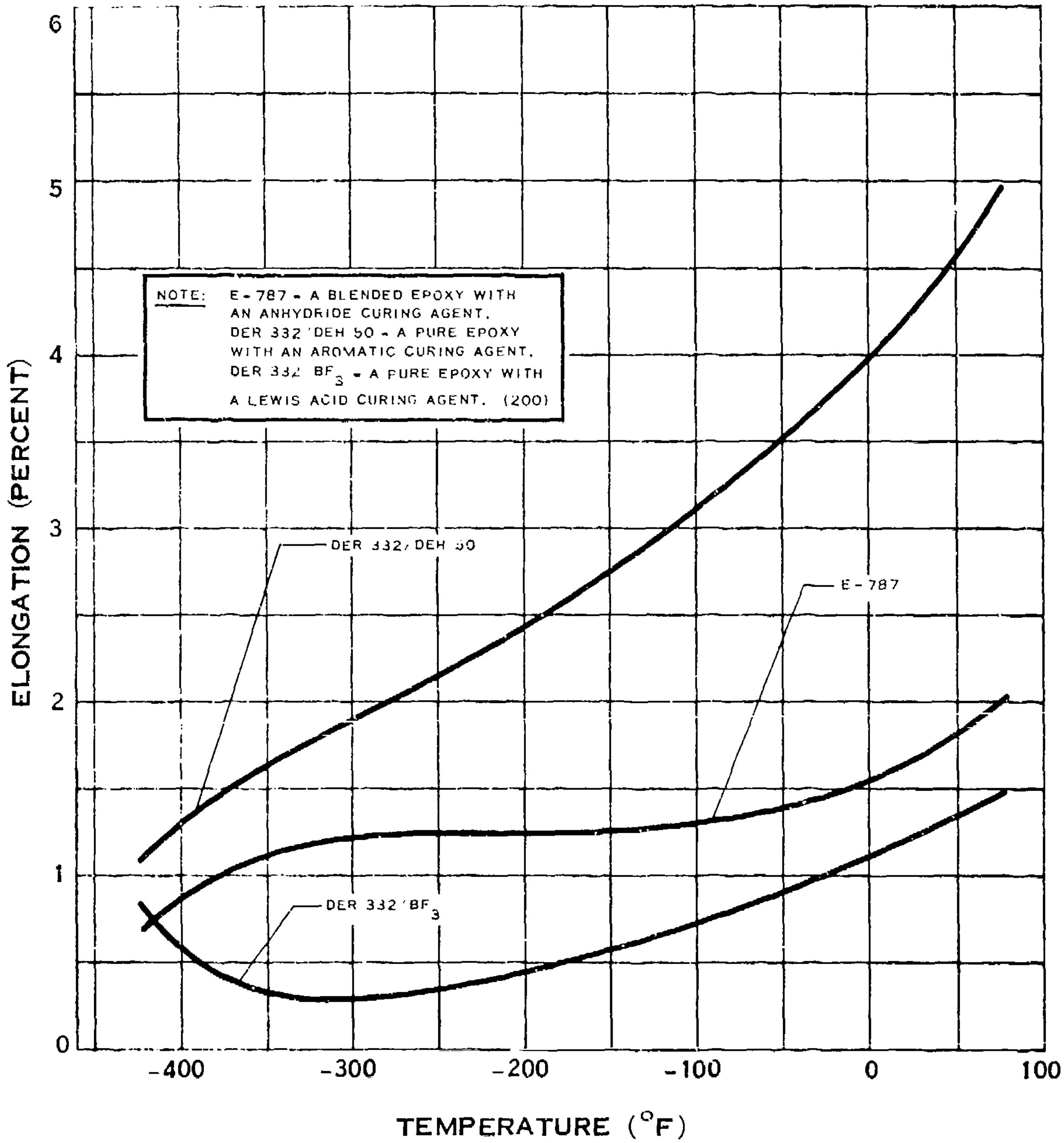
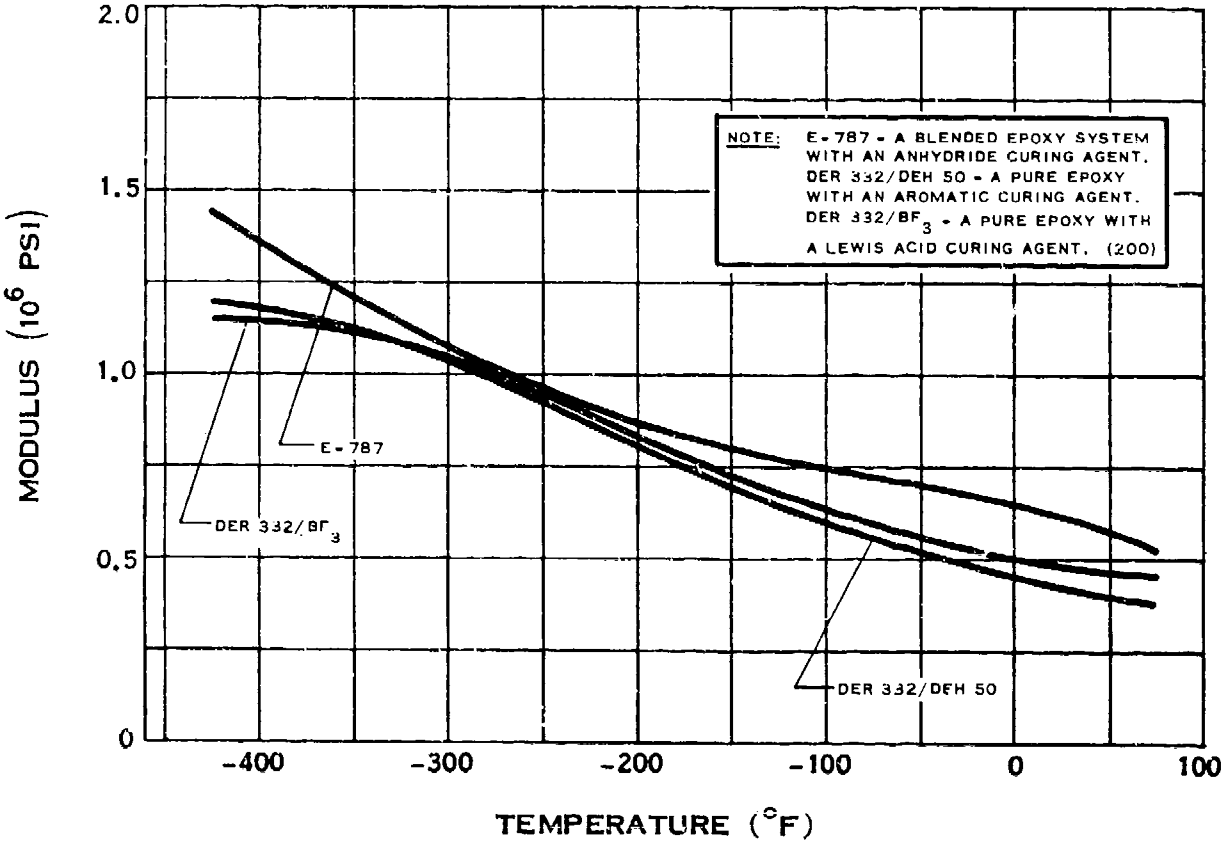


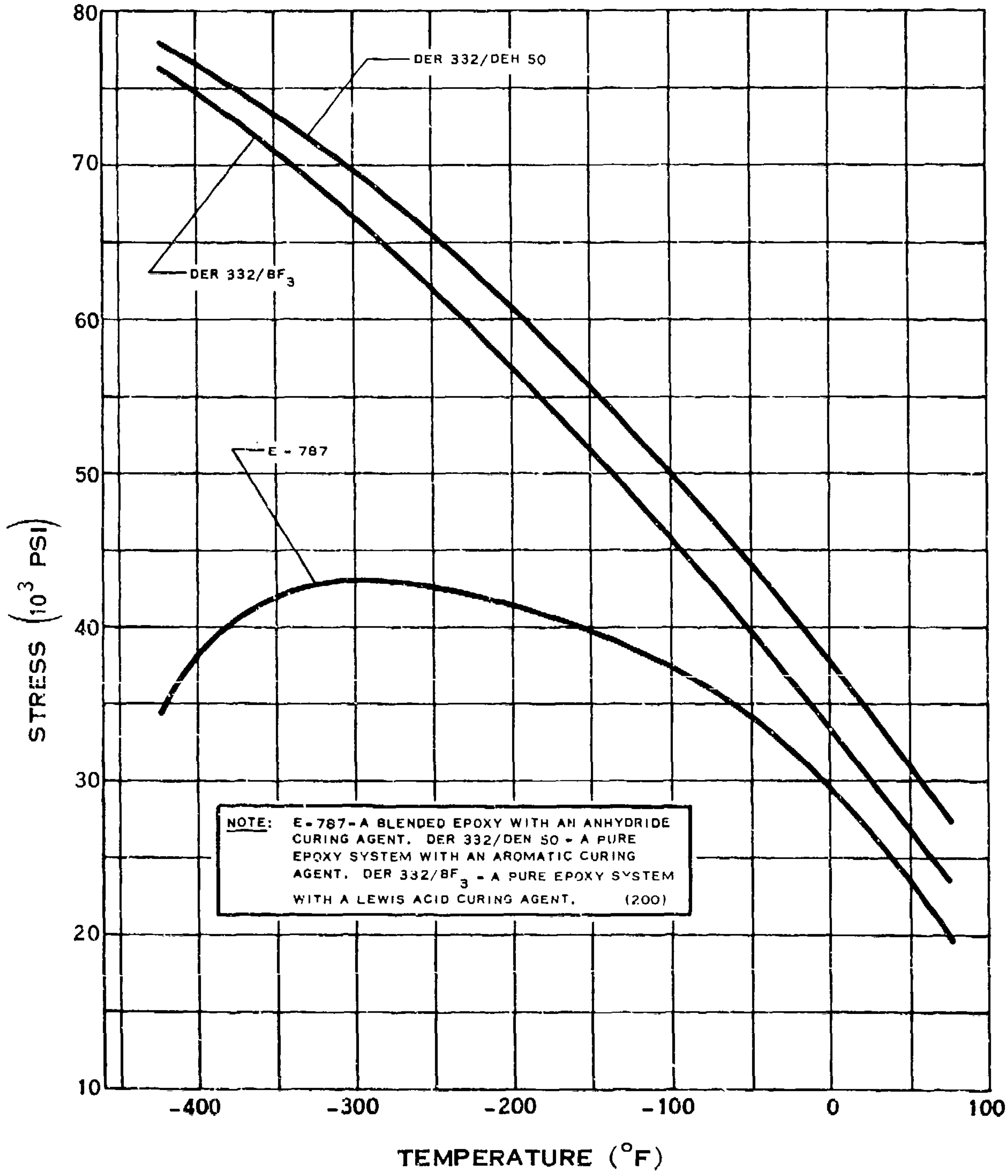
ELONGATION OF CAST EPOXY RESIN

(6-68)



MODULUS OF ELASTICITY OF CAST EPOXY RESIN

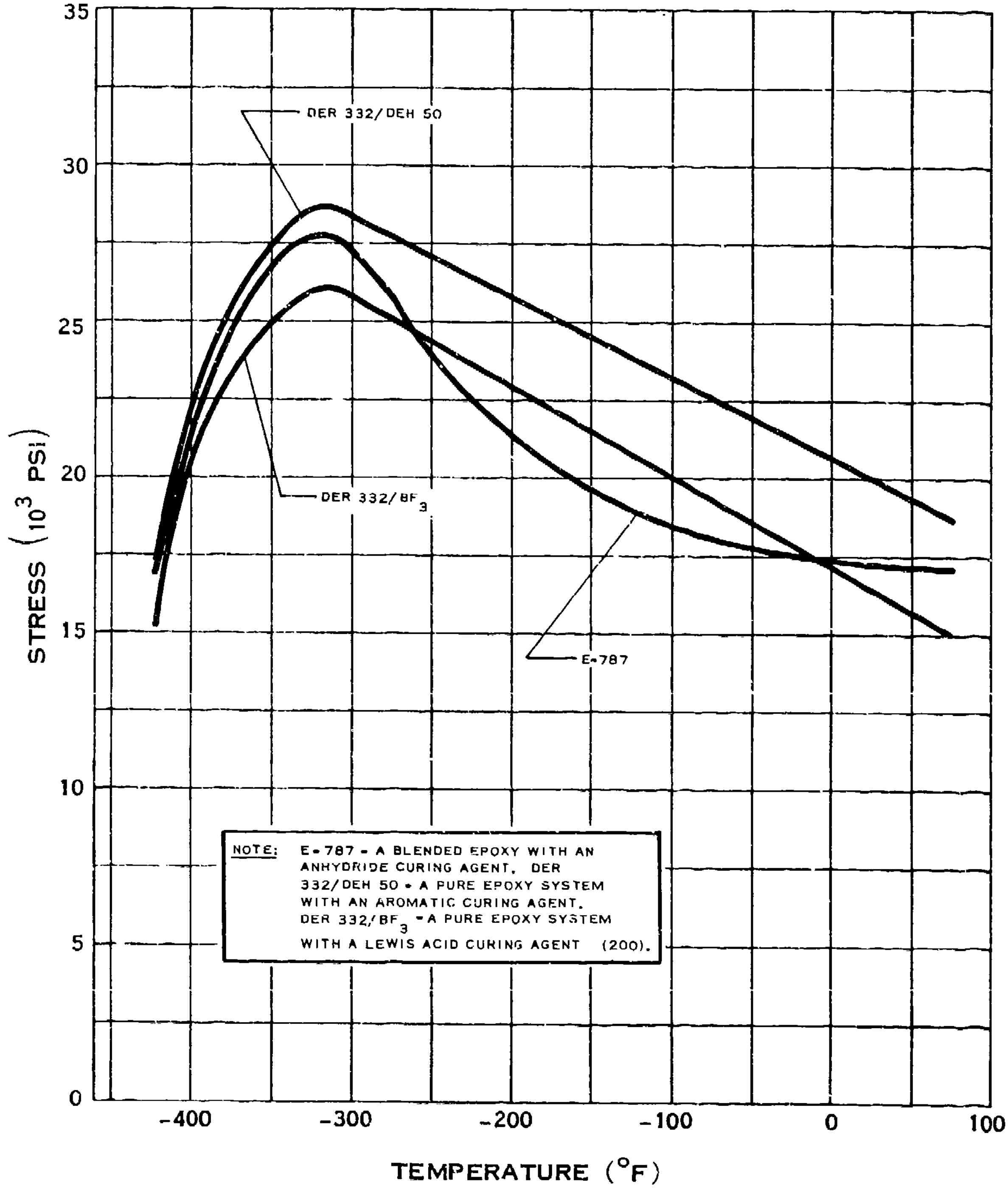
(6-68)



COMPRESSIVE STRENGTH OF CAST EPOXY RESIN

(6-68)

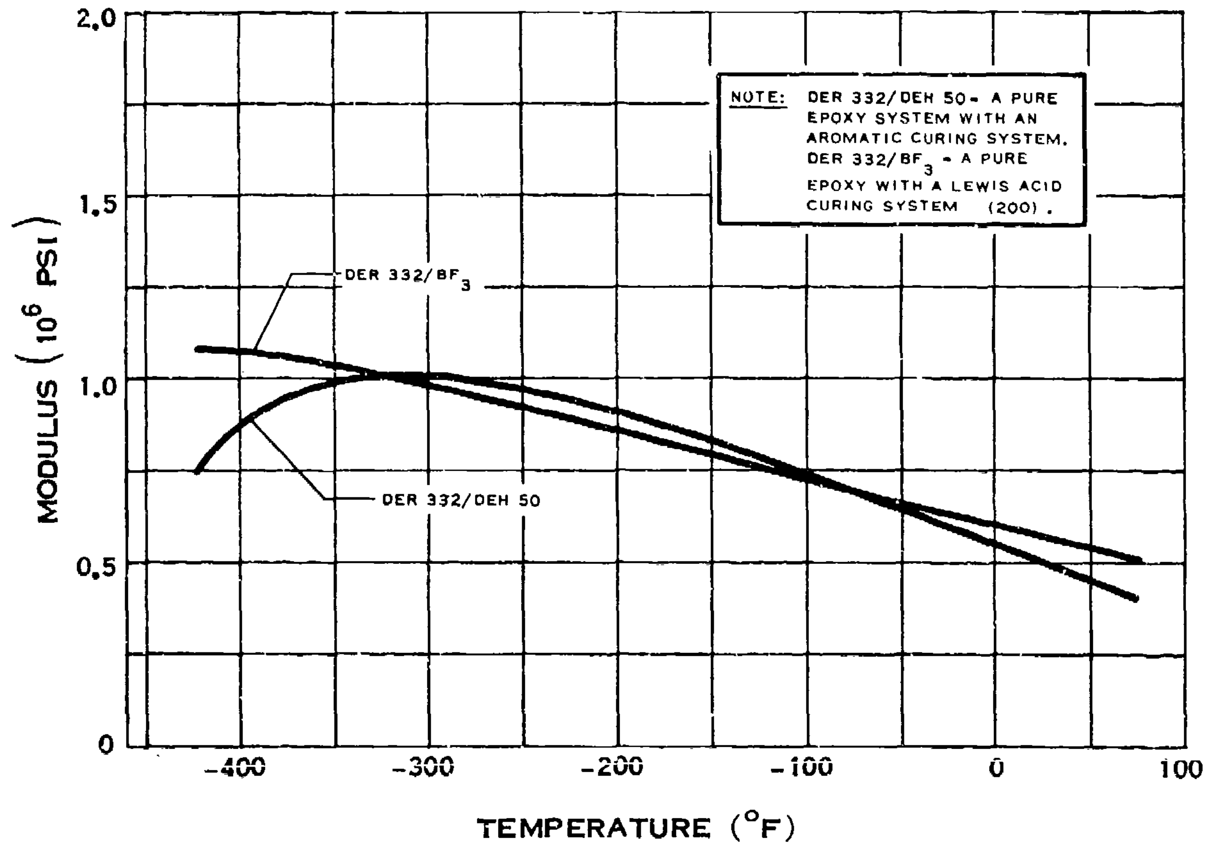
G.5.r



FLEXURAL STRENGTH OF CAST EPOXY RESIN

(6-68)

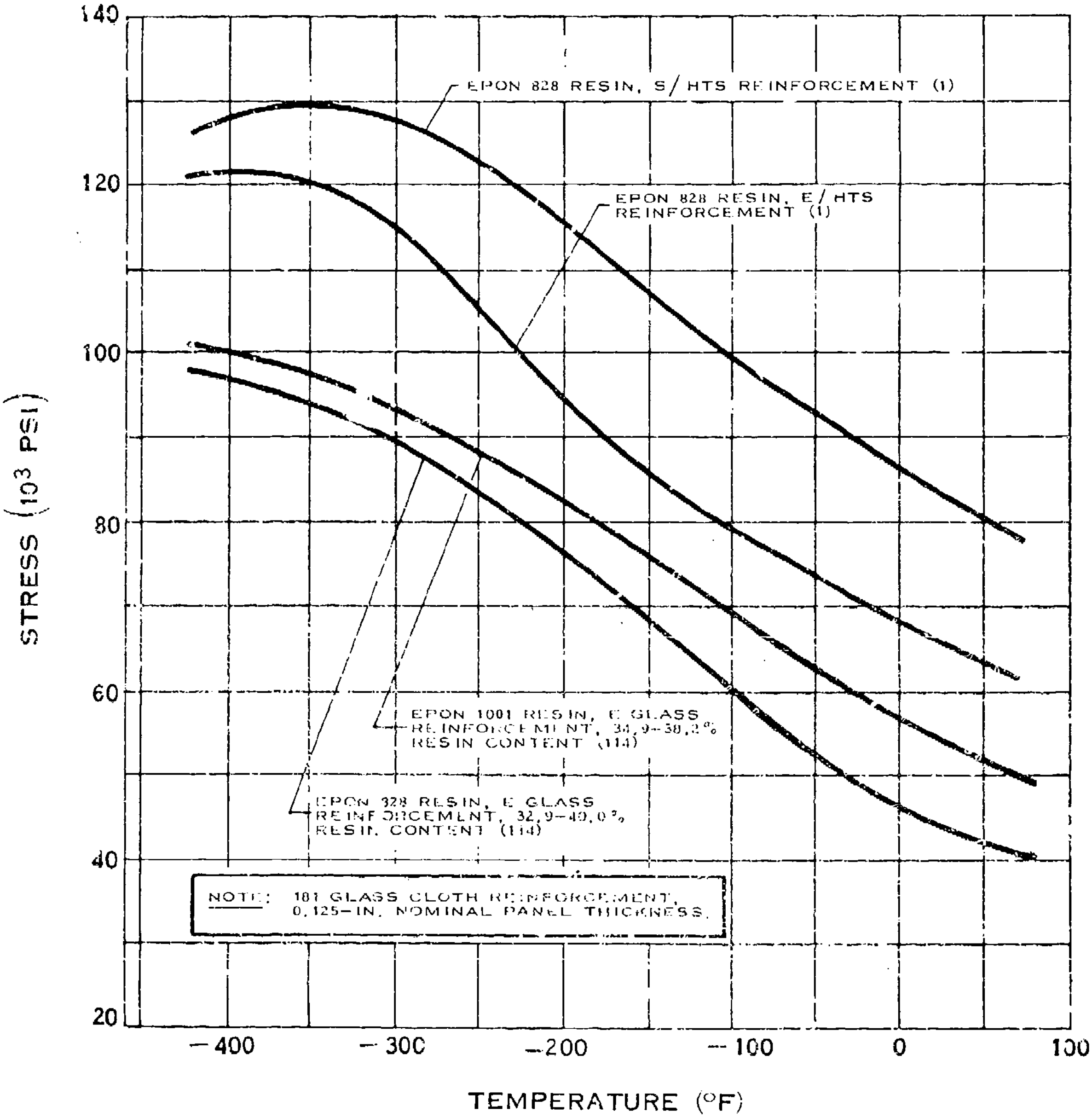
G.5.s



FLEXURAL MODULUS OF CAST EPOXY RESIN

(6-68)

H - FIBER-REINFORCED PLASTICS



TENSILE STRENGTH OF EPOXY – FIBERGLAS LAMINATE

(1-65)

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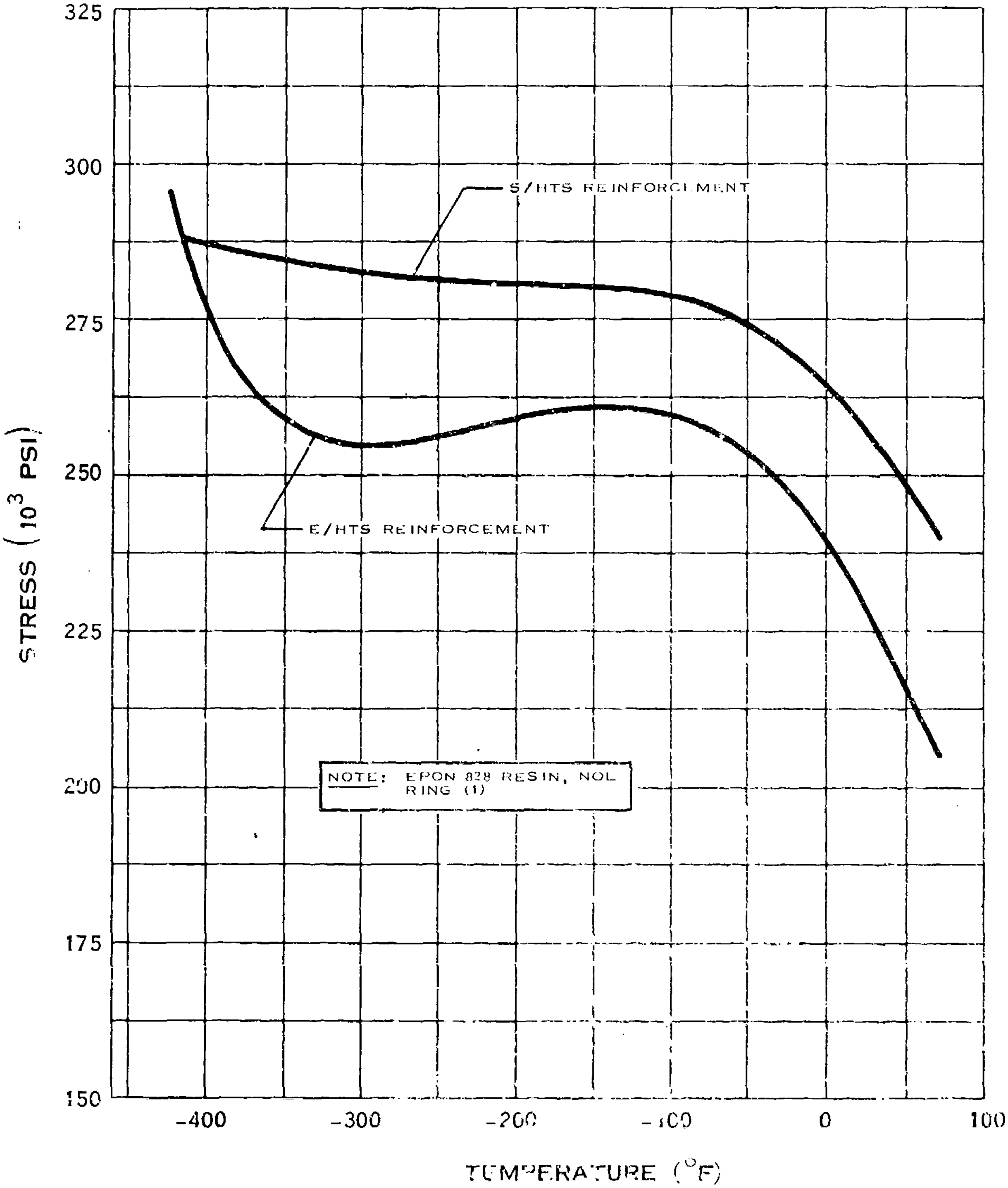
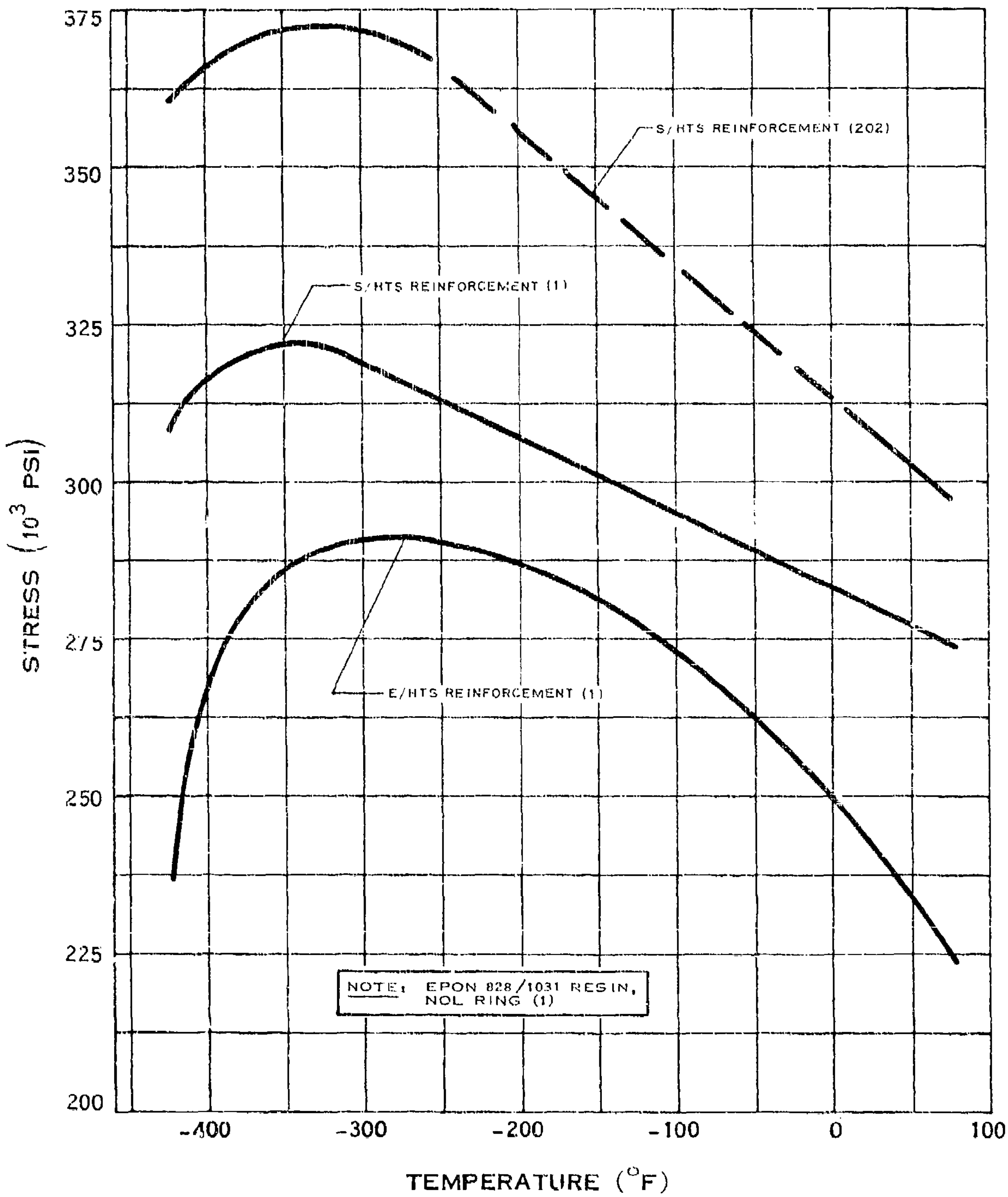


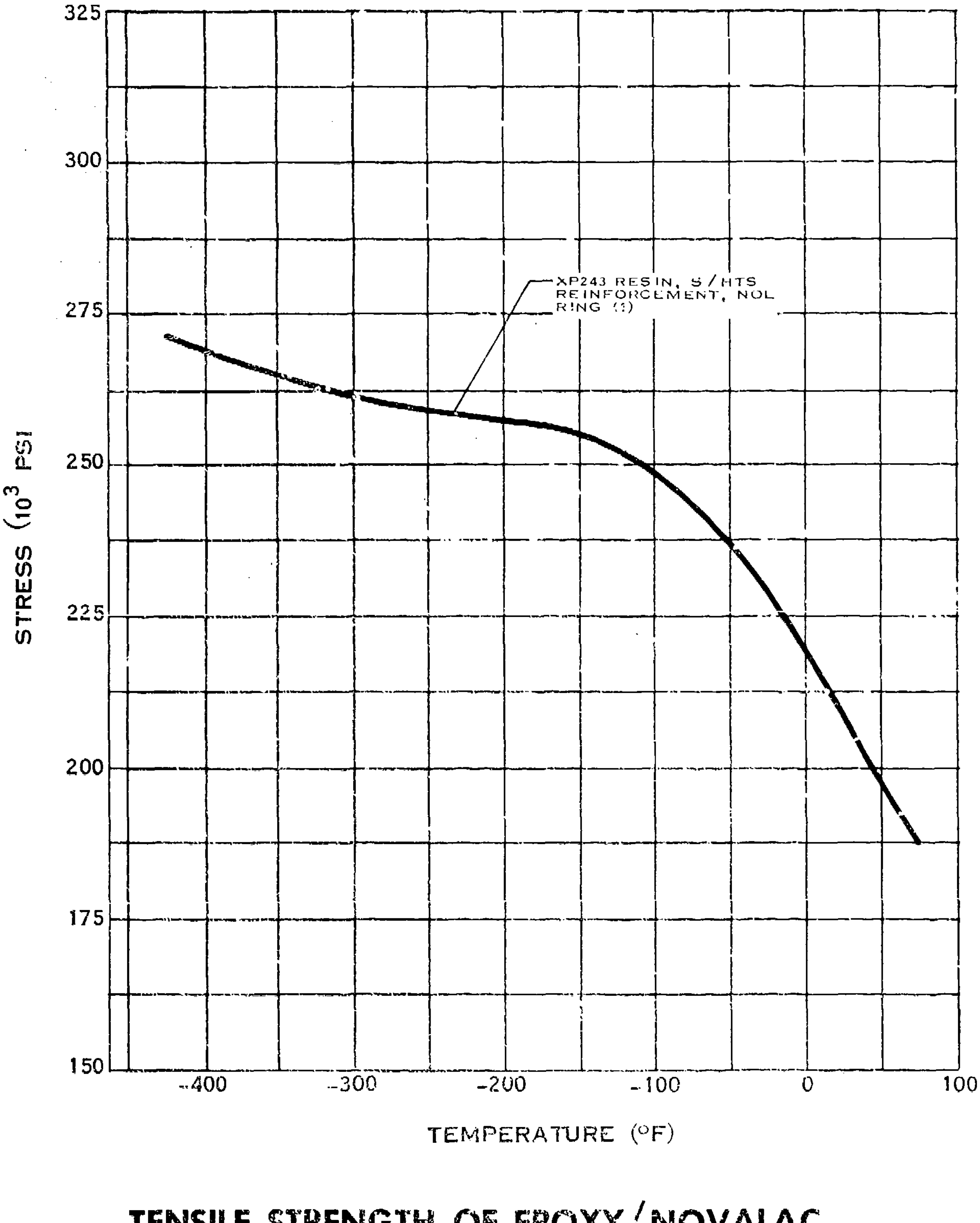
TENSILE STRENGTH OF EPOXY-FIBERGLAS FILAMENT WOUND RINGS

(1-65)



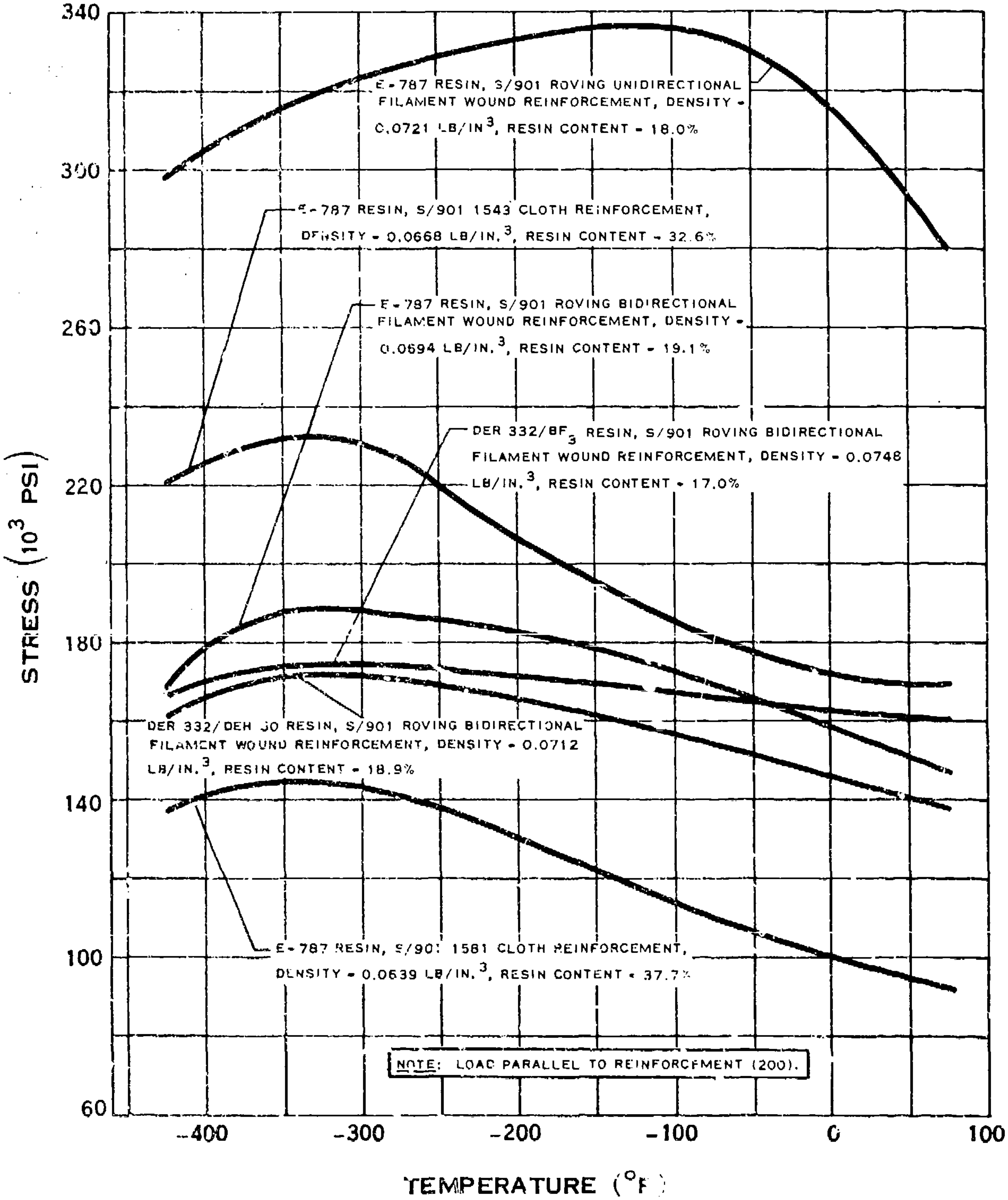
TENSILE STRENGTH OF EPOXY-FIBERGLAS FILAMENT WOUND RINGS

(6-63)

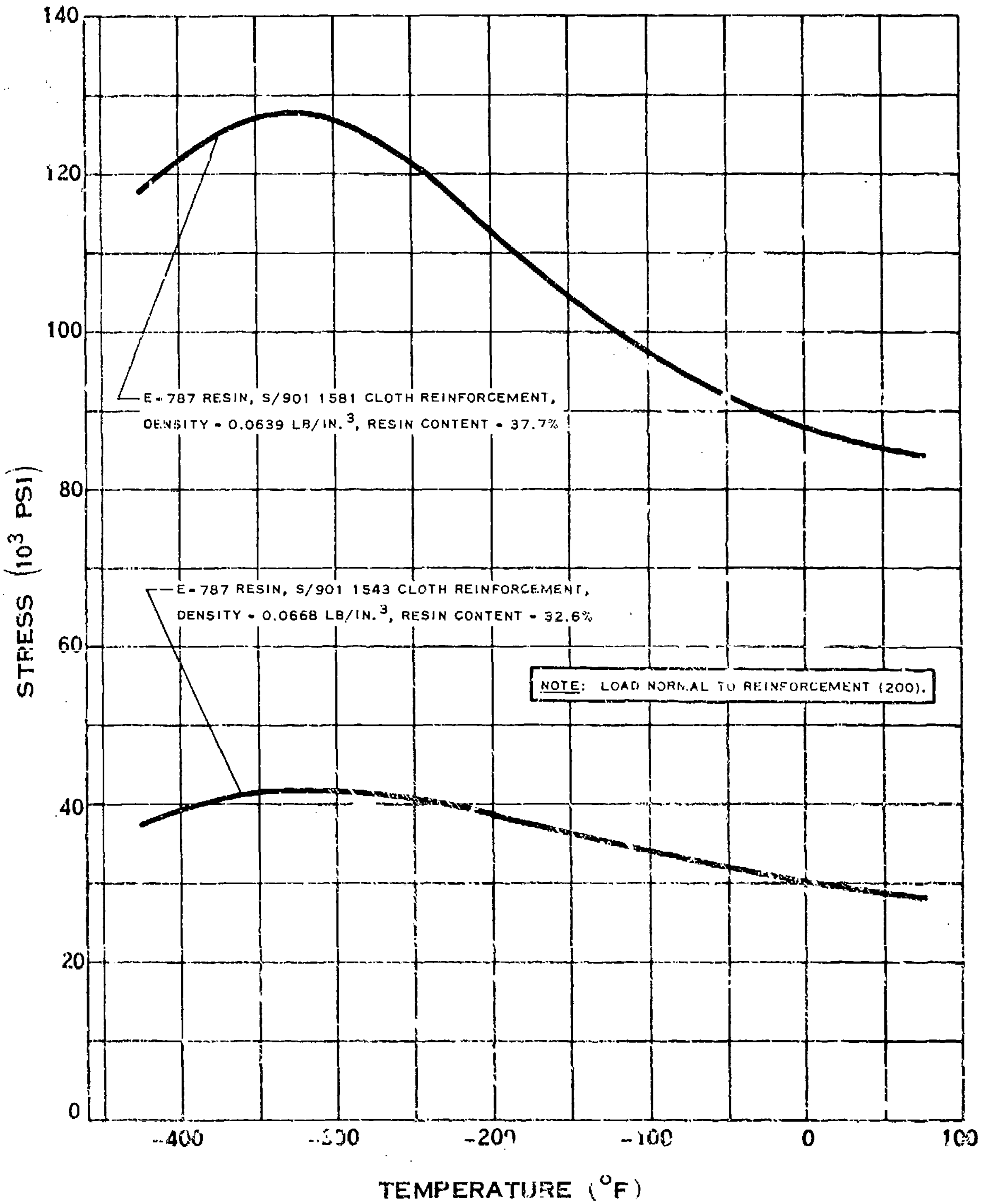


TENSILE STRENGTH OF EPOXY/NOVALAC FIBERGLAS FILAMENT WOUND RINGS

(1-65)

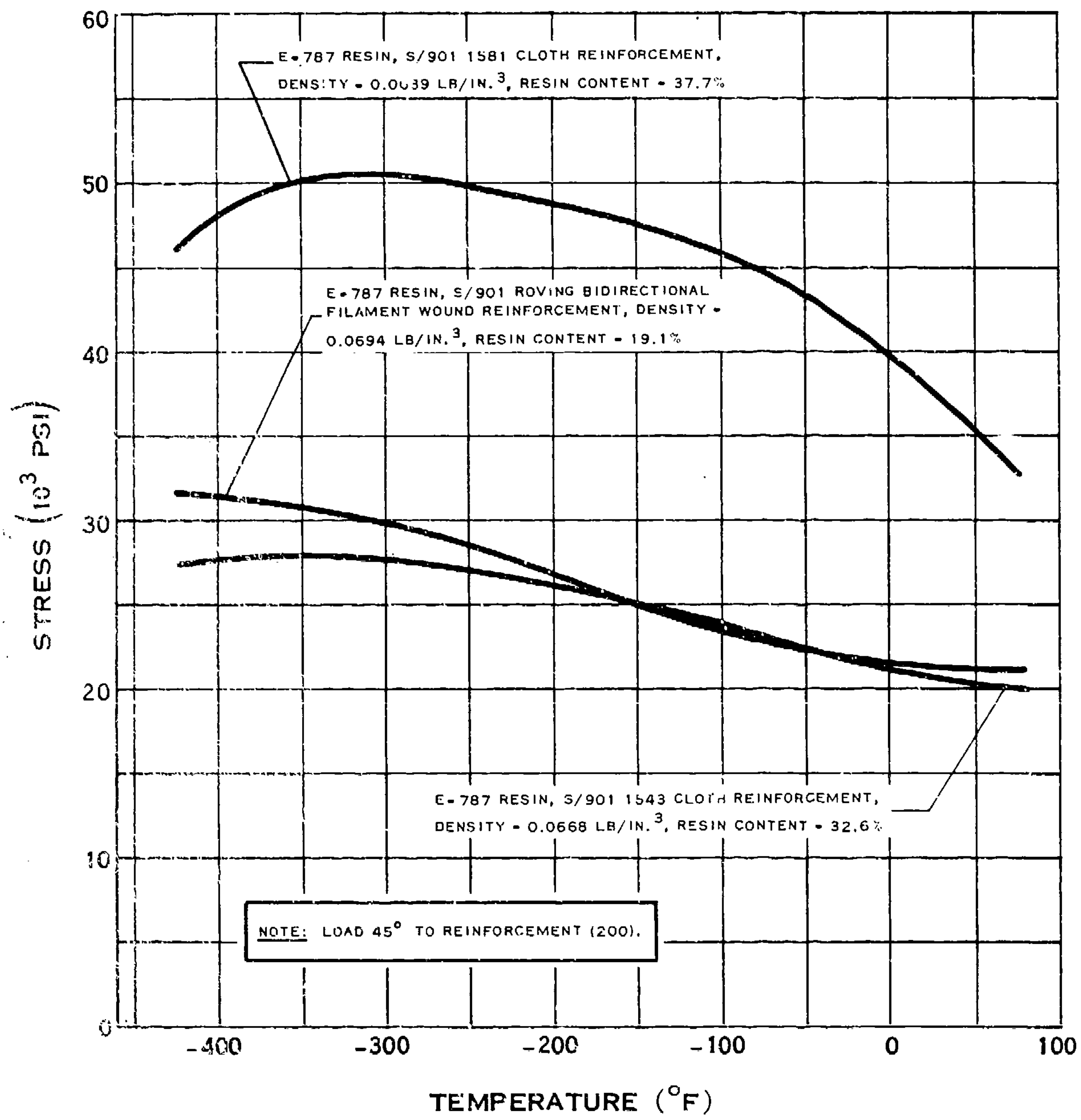


TENSILE STRENGTH OF EPOXY-FIBERGLAS LAMINATE



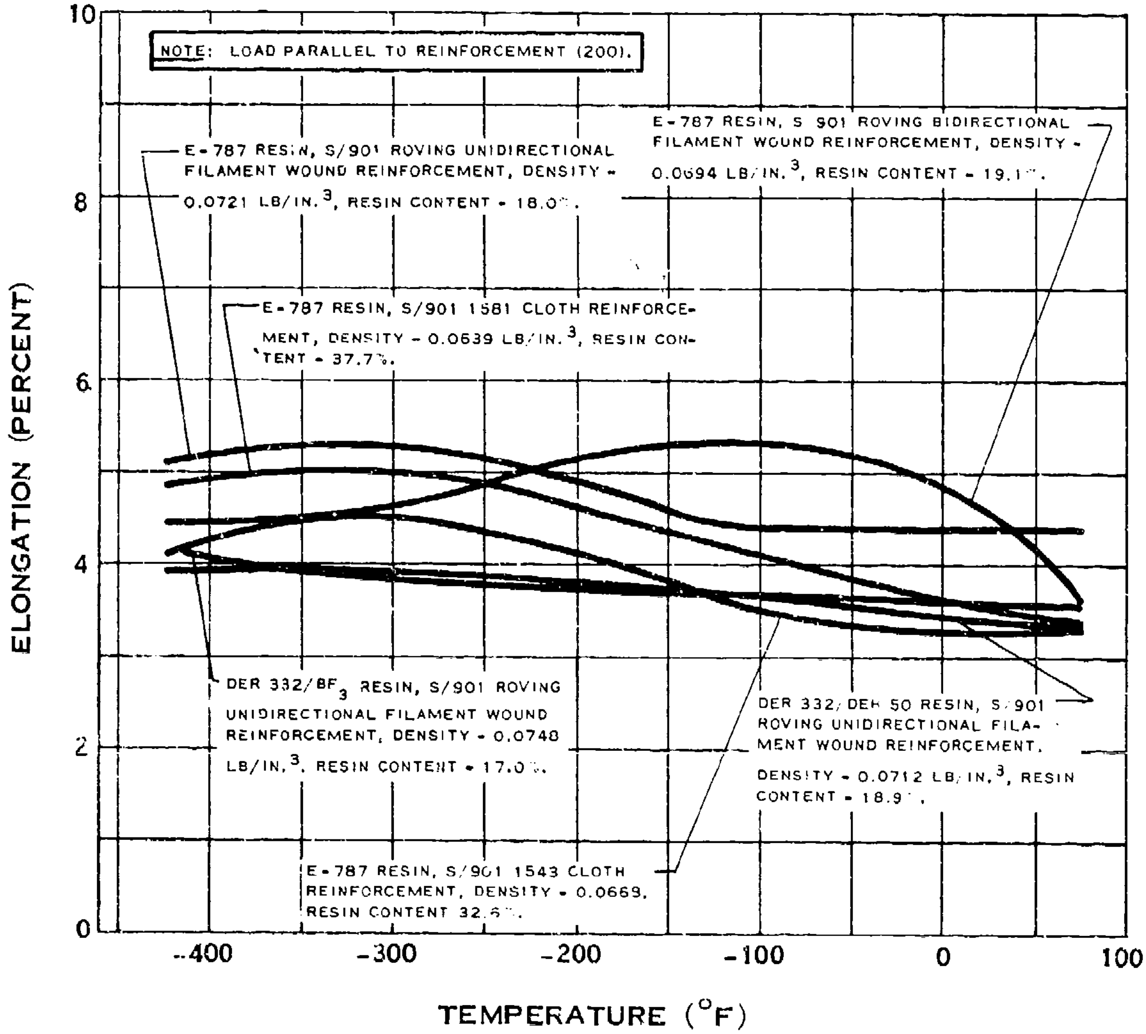
TENSILE STRENGTH OF EPOXY-FIBERGLAS LAMINATE

(6-68)



TENSILE STRENGTH OF EPOXY-FIBERGLAS LAMINATE

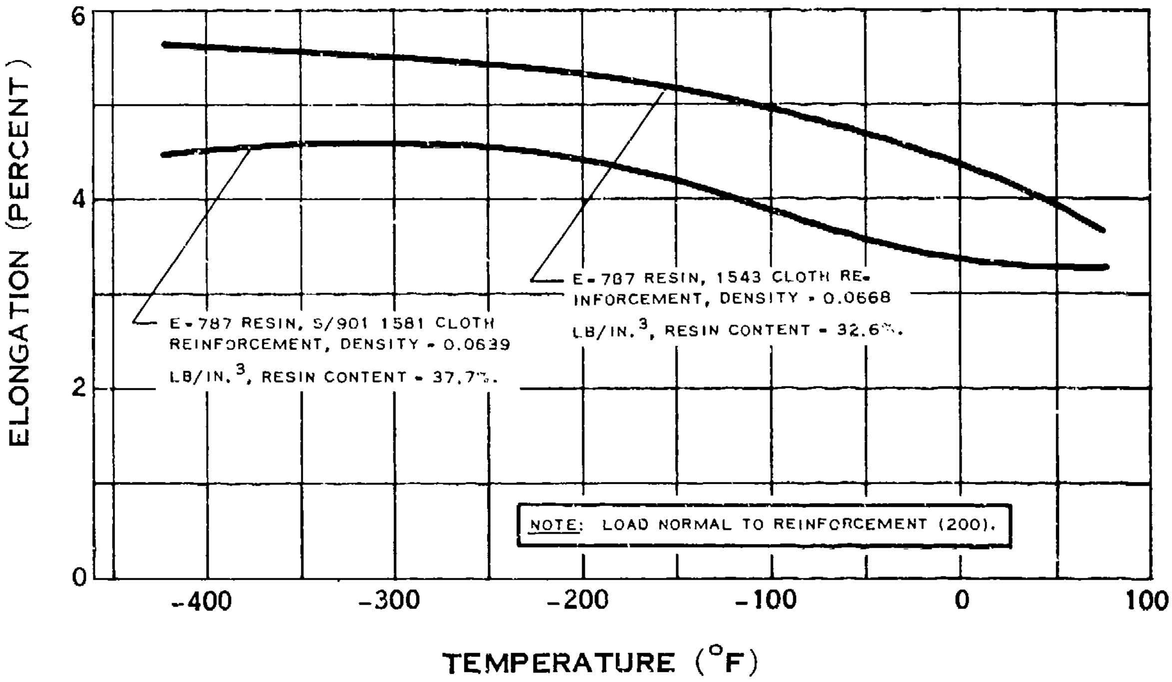
(6-68)



ELONGATION OF EPOXY-FIBERGLAS LAMINATE

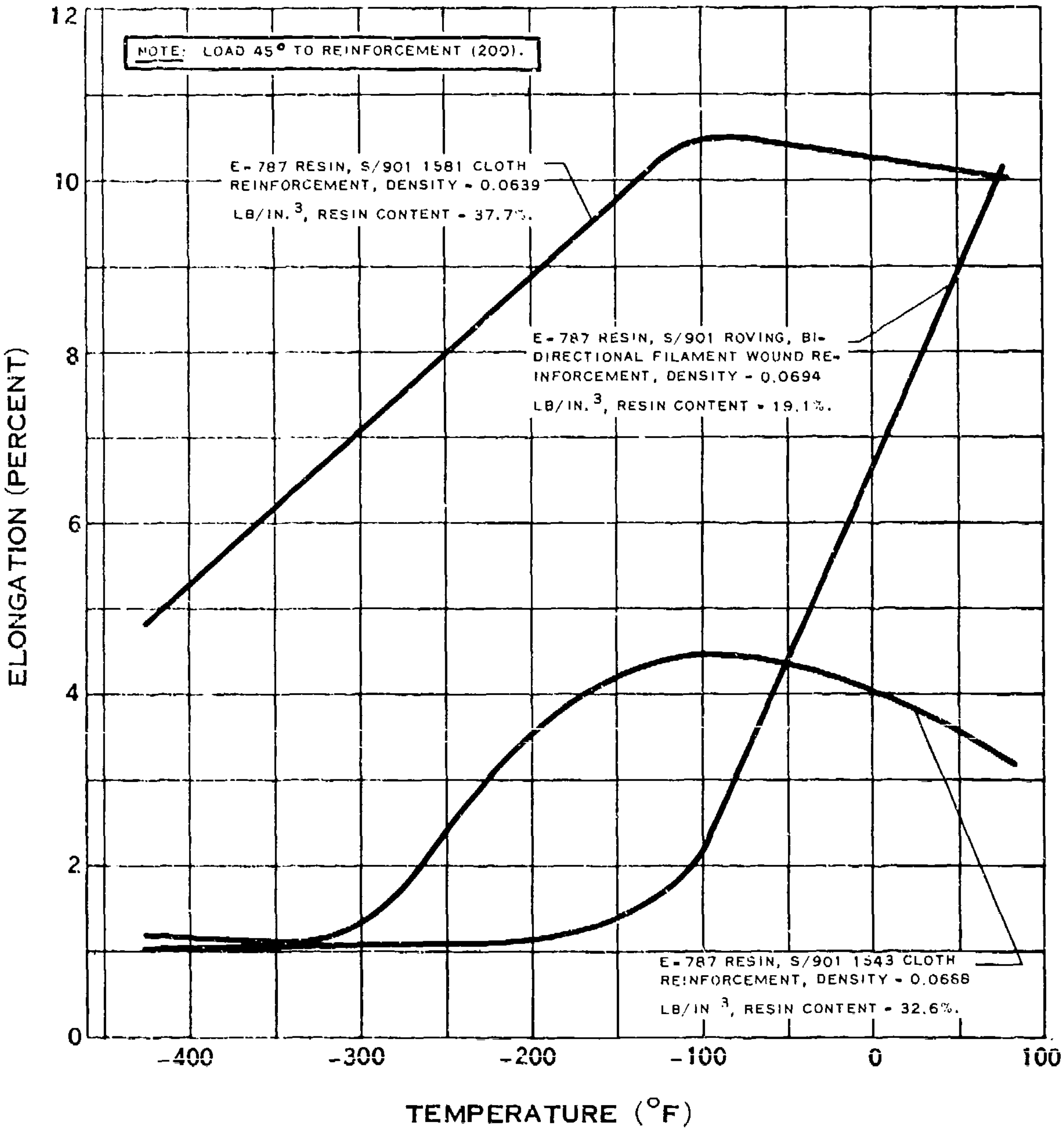
(6-68)

H.1.c-1



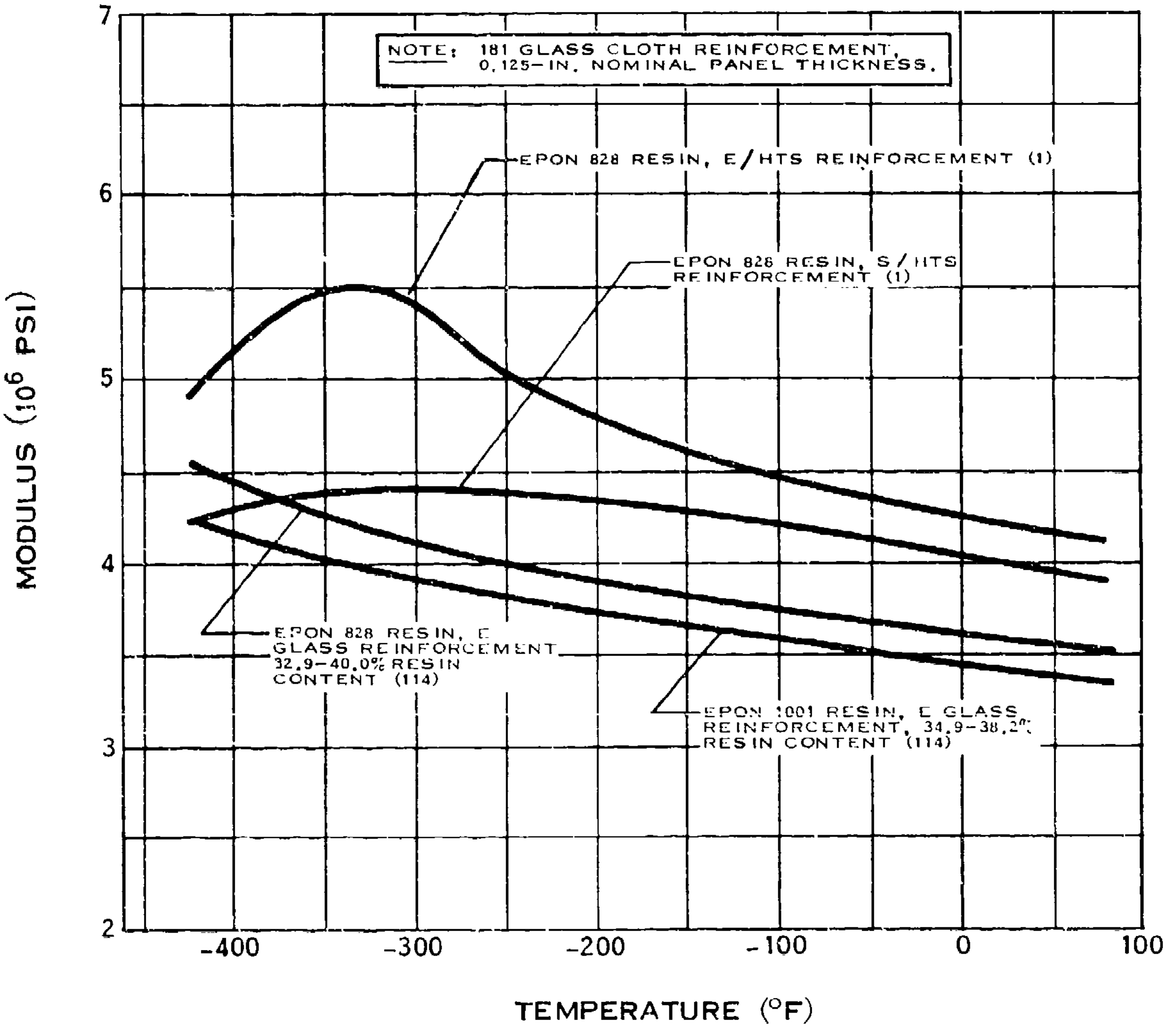
ELONGATION OF EPOXY-FIBERGLAS LAMINATE

(6-68)



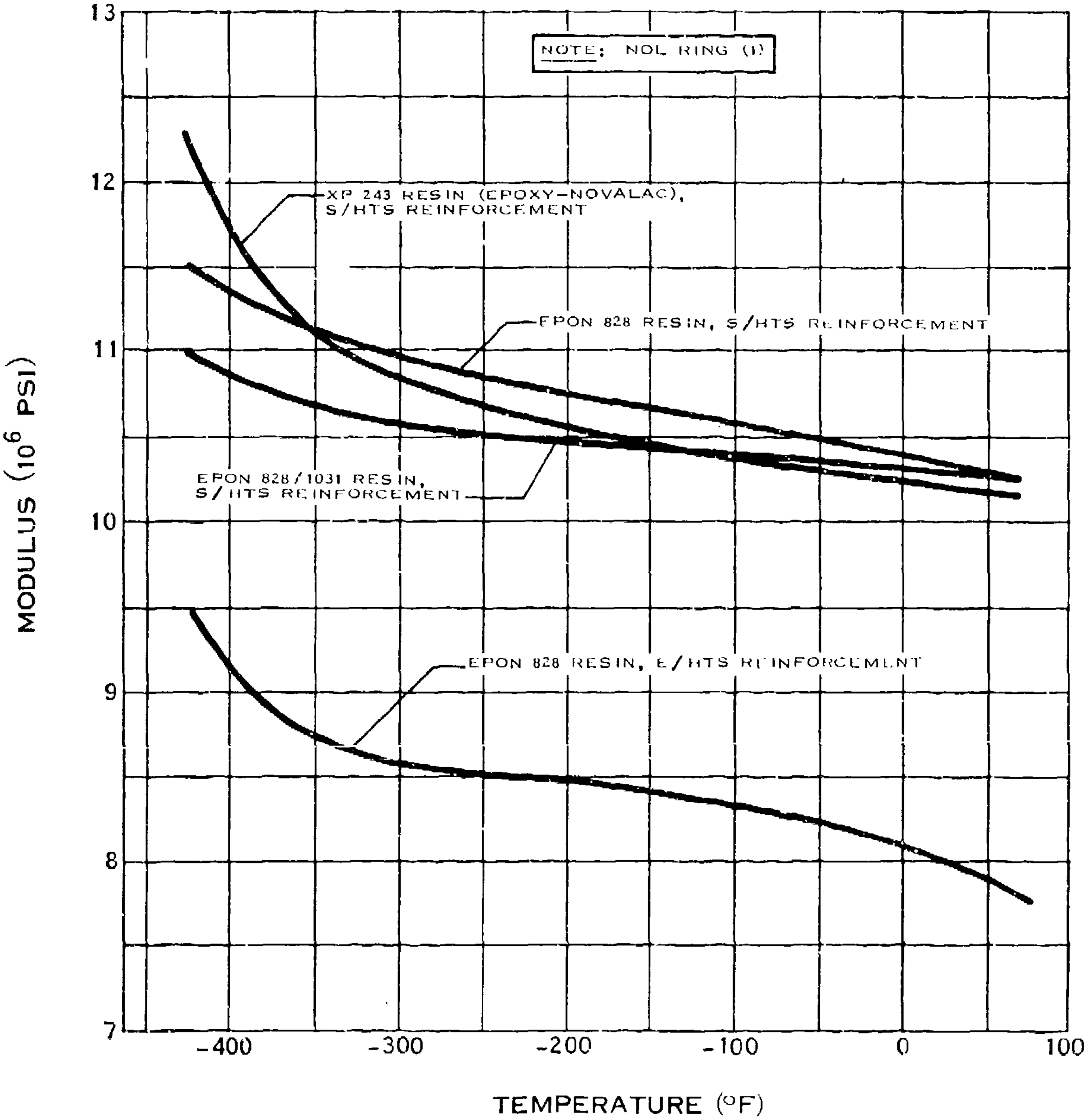
ELONGATION OF EPOXY-FIBERGLAS LAMINATE

(6-68)

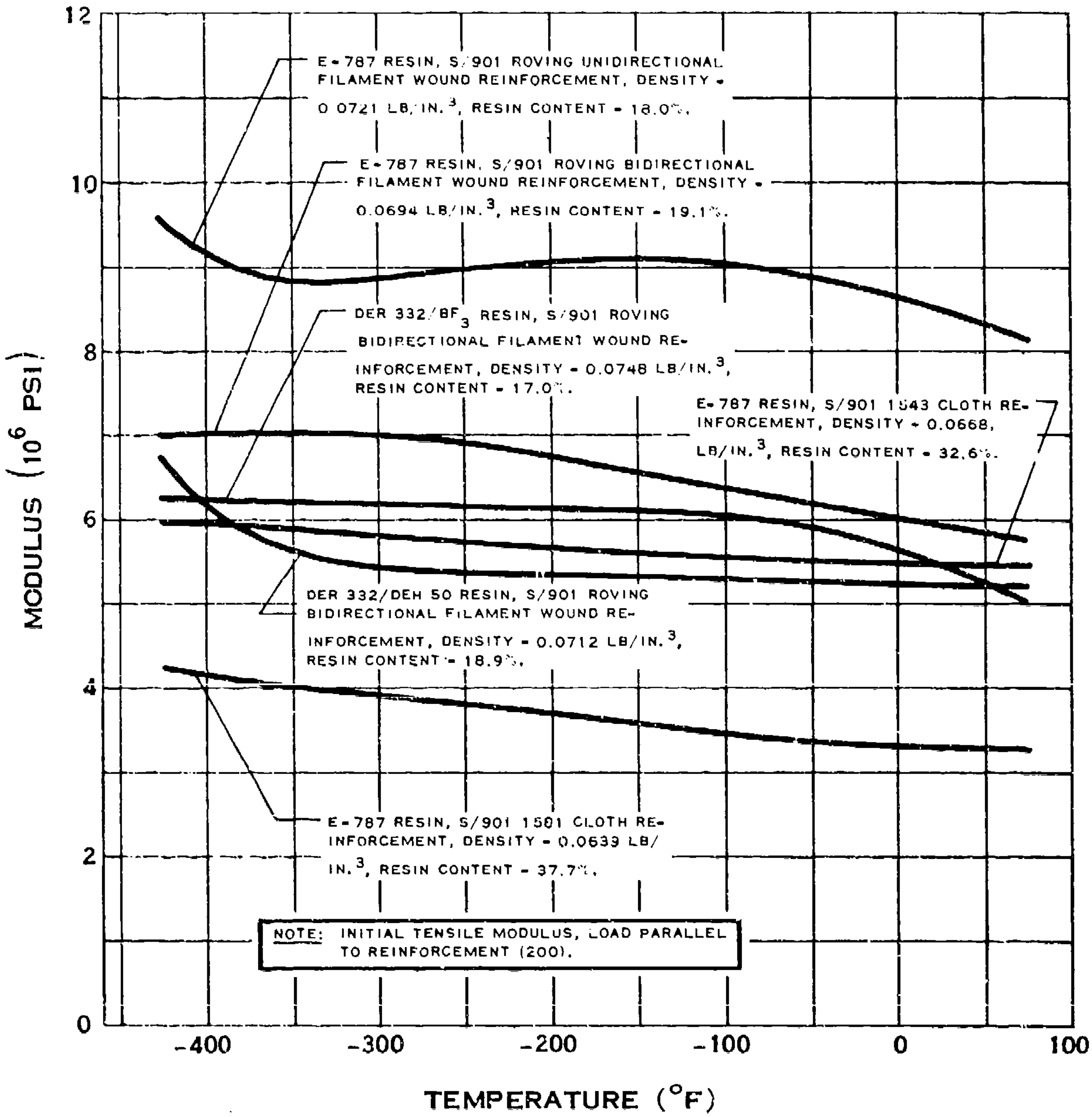


MODULUS OF ELASTICITY OF EPOXY-FIBERGLAS LAMINATE

(1-65)

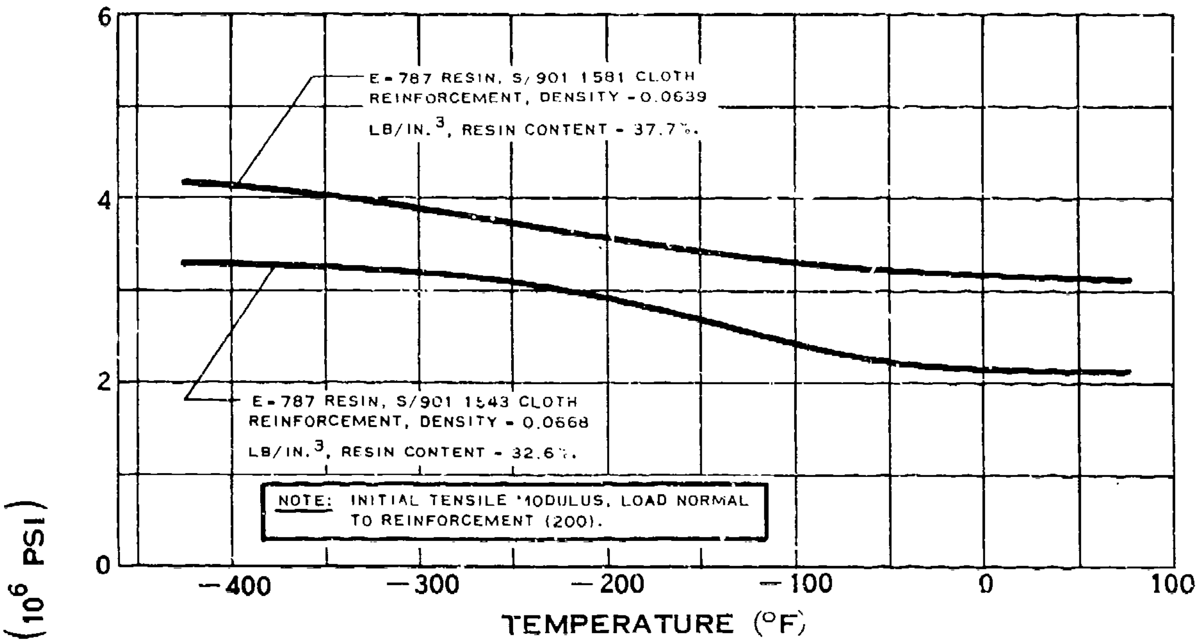


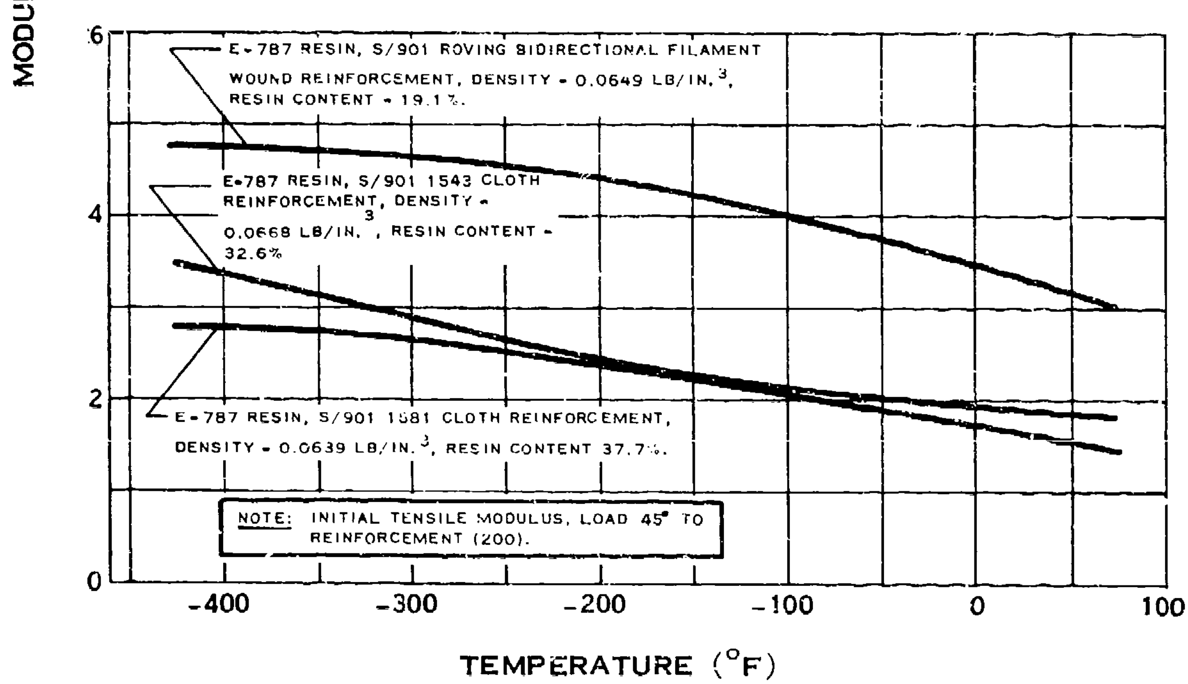
MODULUS OF ELASTICITY OF EPOXY AND EPOXY-NOVALAC FIBERGLAS FILAMENT WOUND RINGS



MODULUS OF ELASTICITY OF EPOXY-FIBERGLAS LAMINATE

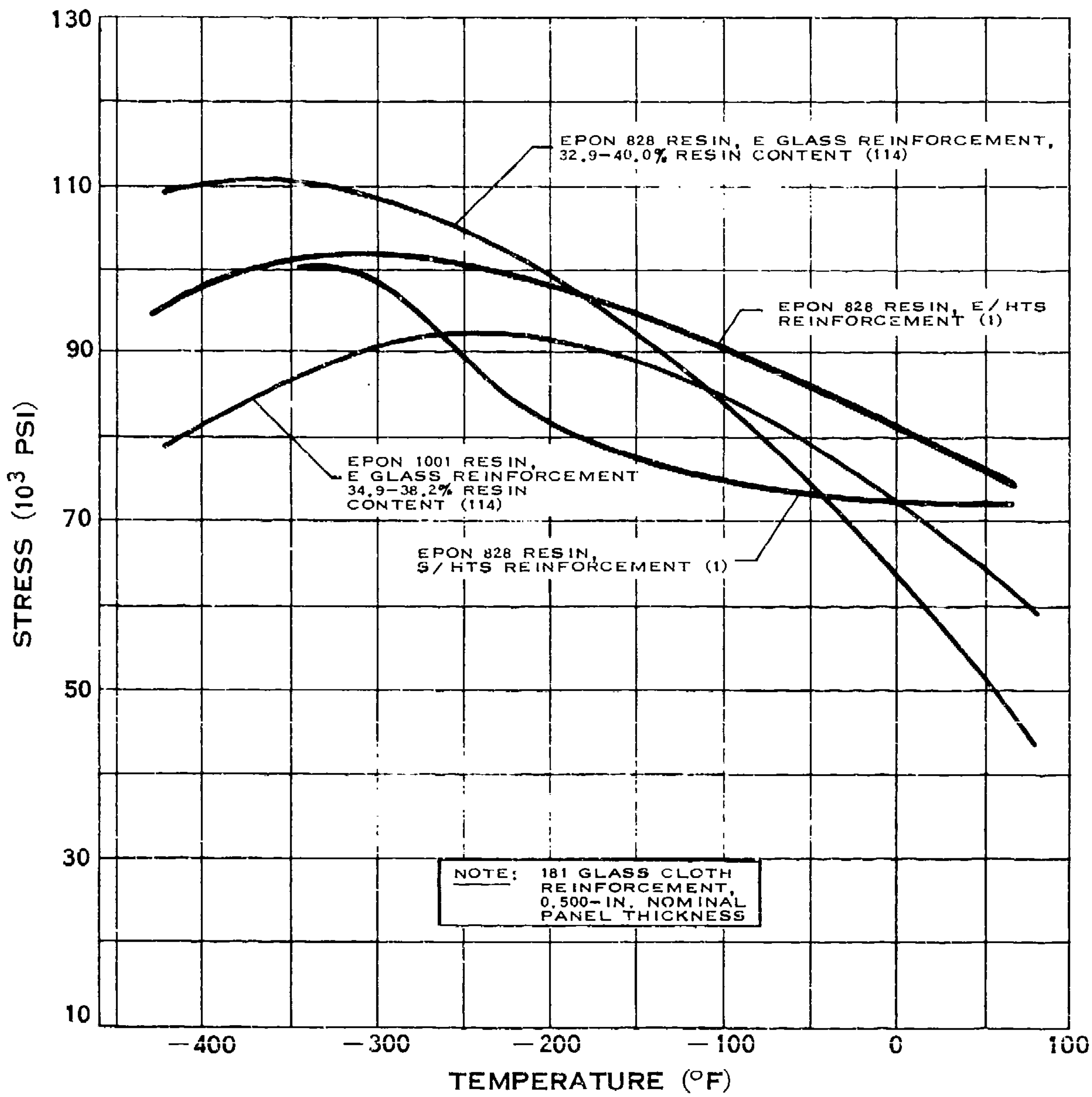
(6-68)





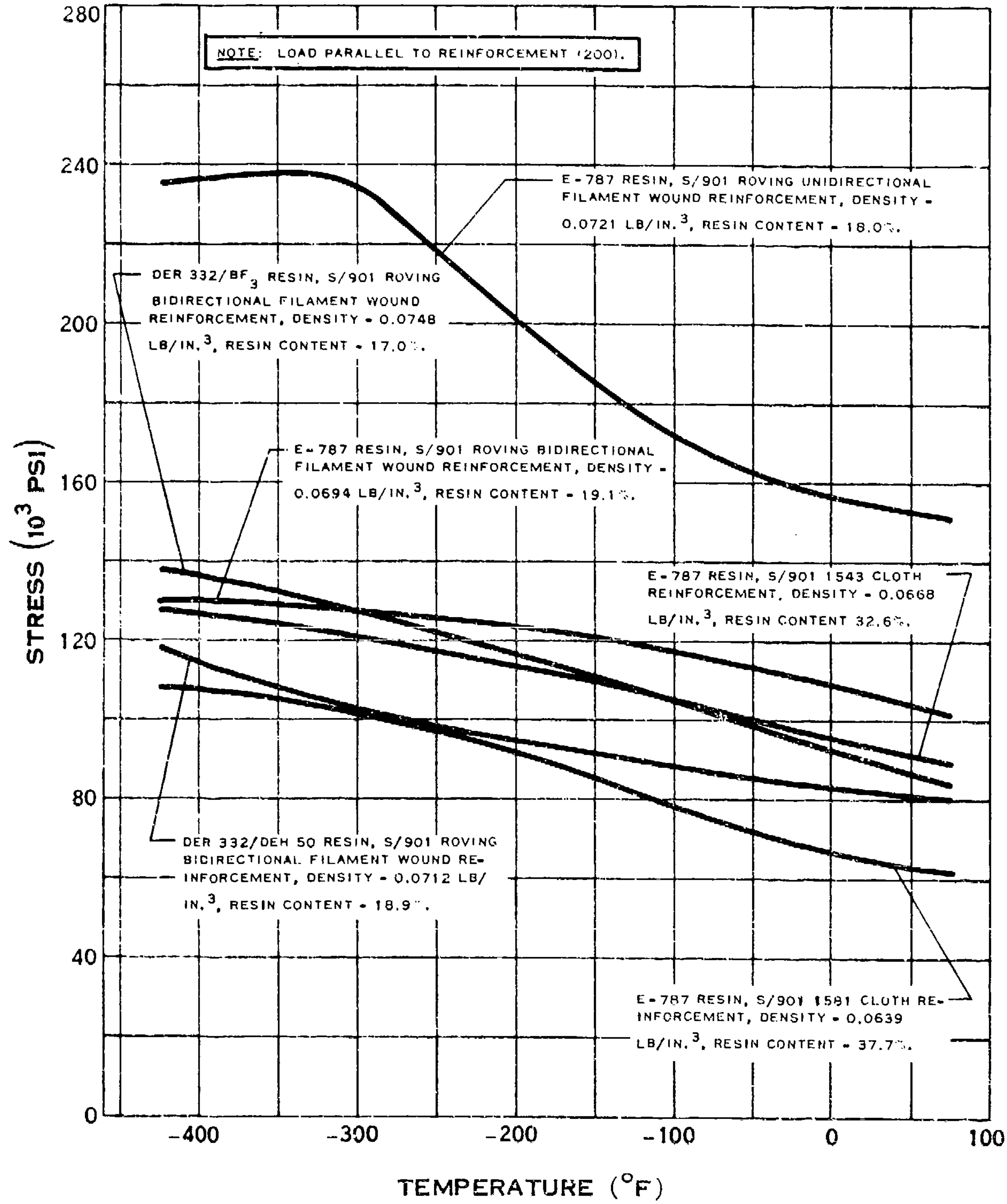
MODULUS OF ELASTICITY OF EPOXY-FIBERGLAS LAMINATE

(6-68)



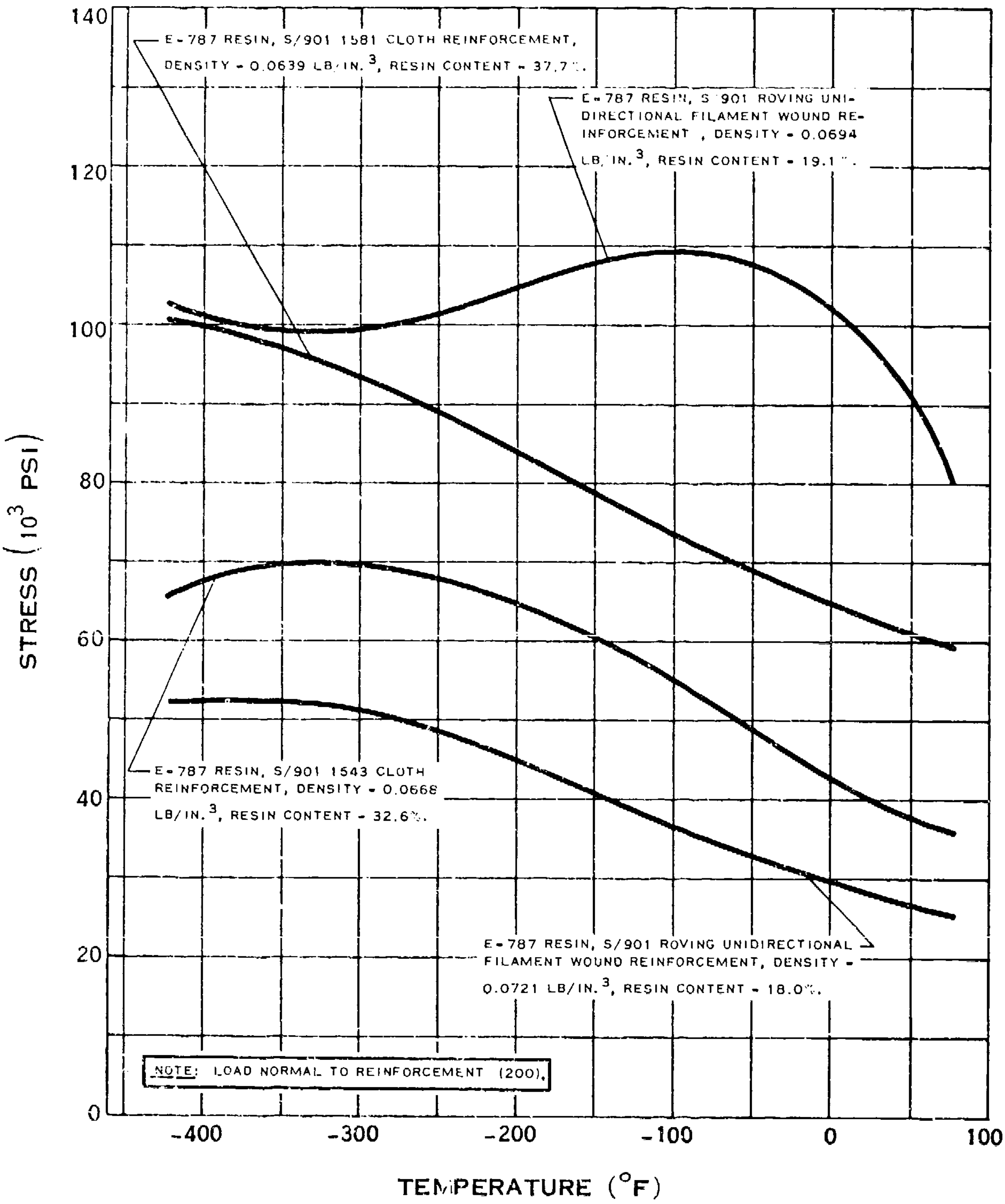
COMPRESSIVE STRENGTH OF EPOXY – FIBERGLAS LAMINATE

(1−65)



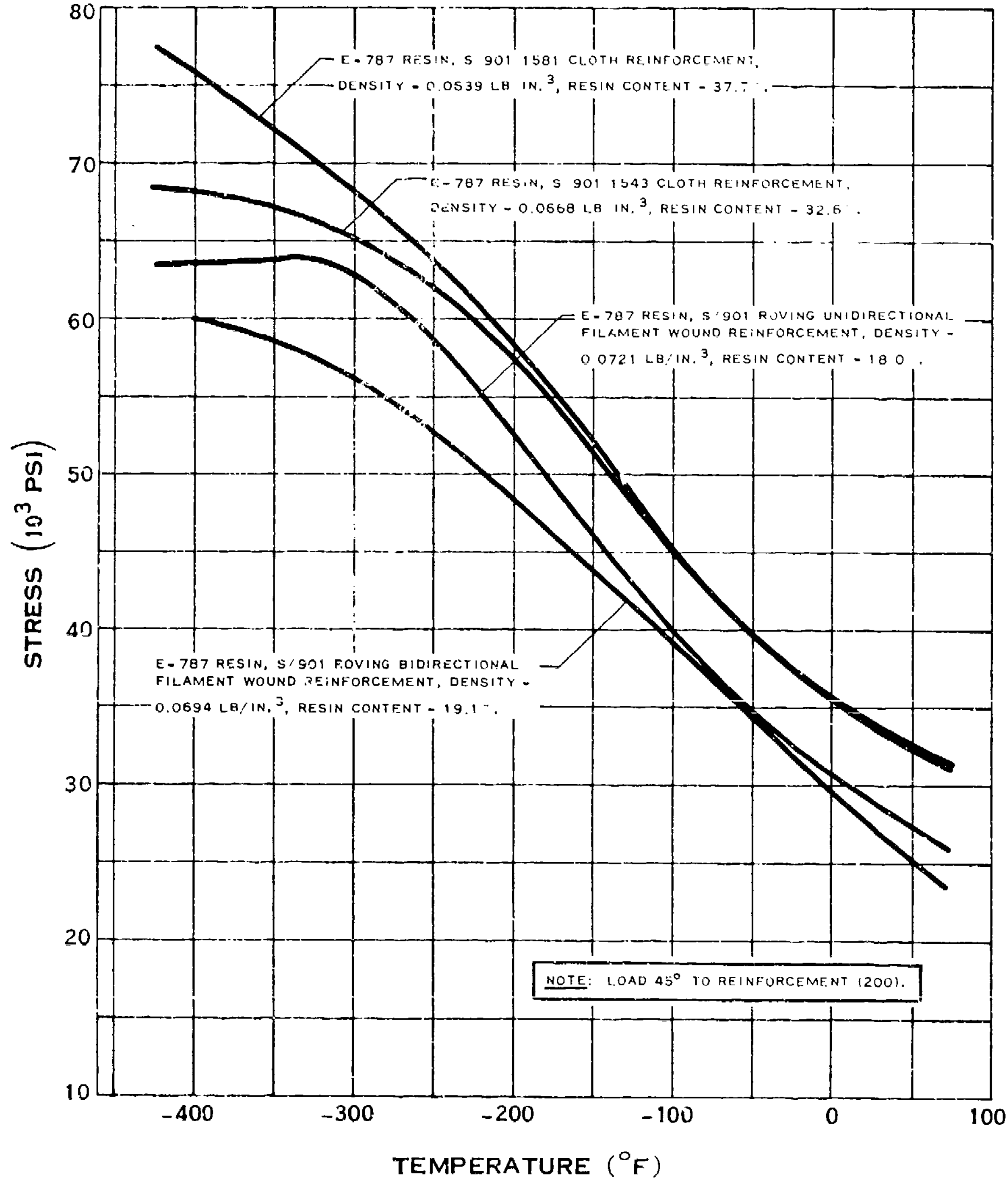
COMPRESSIVE STRENGTH OF EPOXY-FIBERGLAS LAMINATE

(6-68)



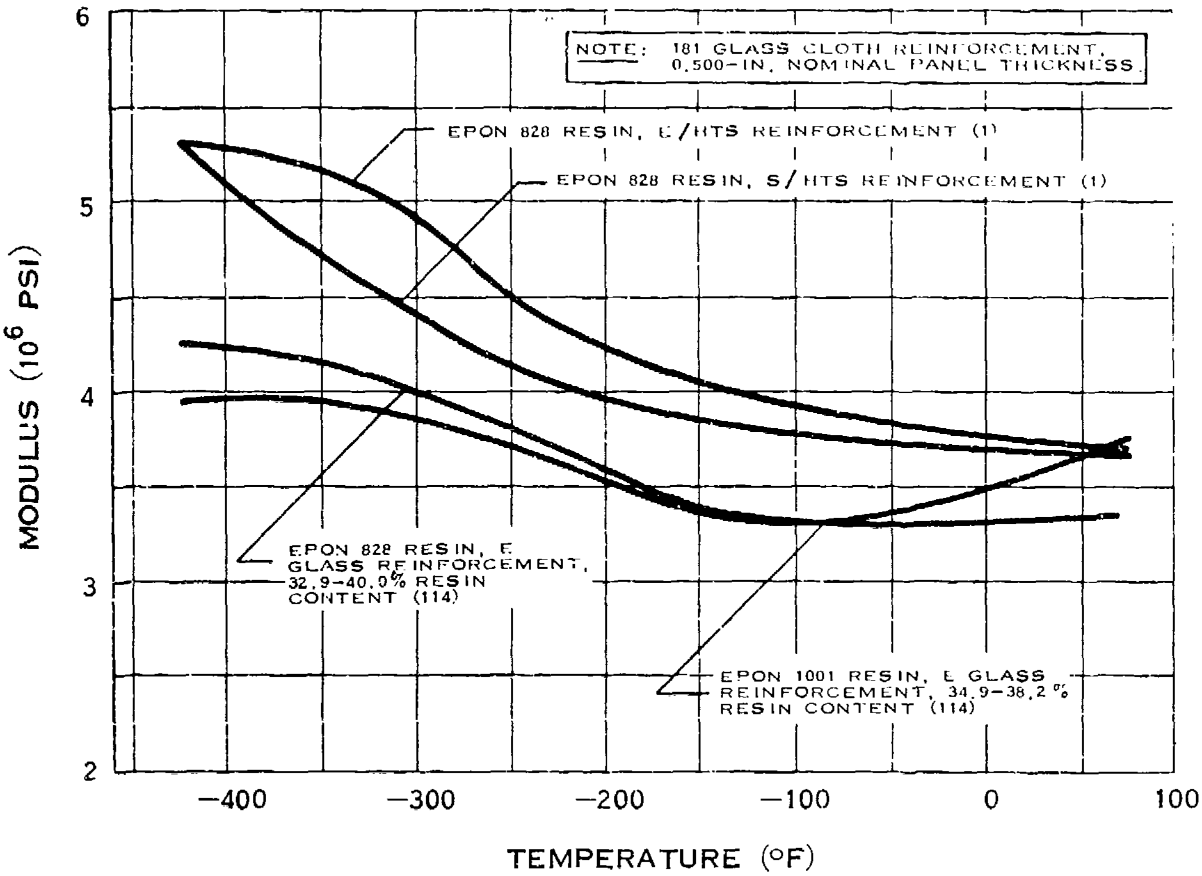
COMPRESSIVE STRENGTH OF EPOXY-FIBERGLAS LAMINATE

(6-68)



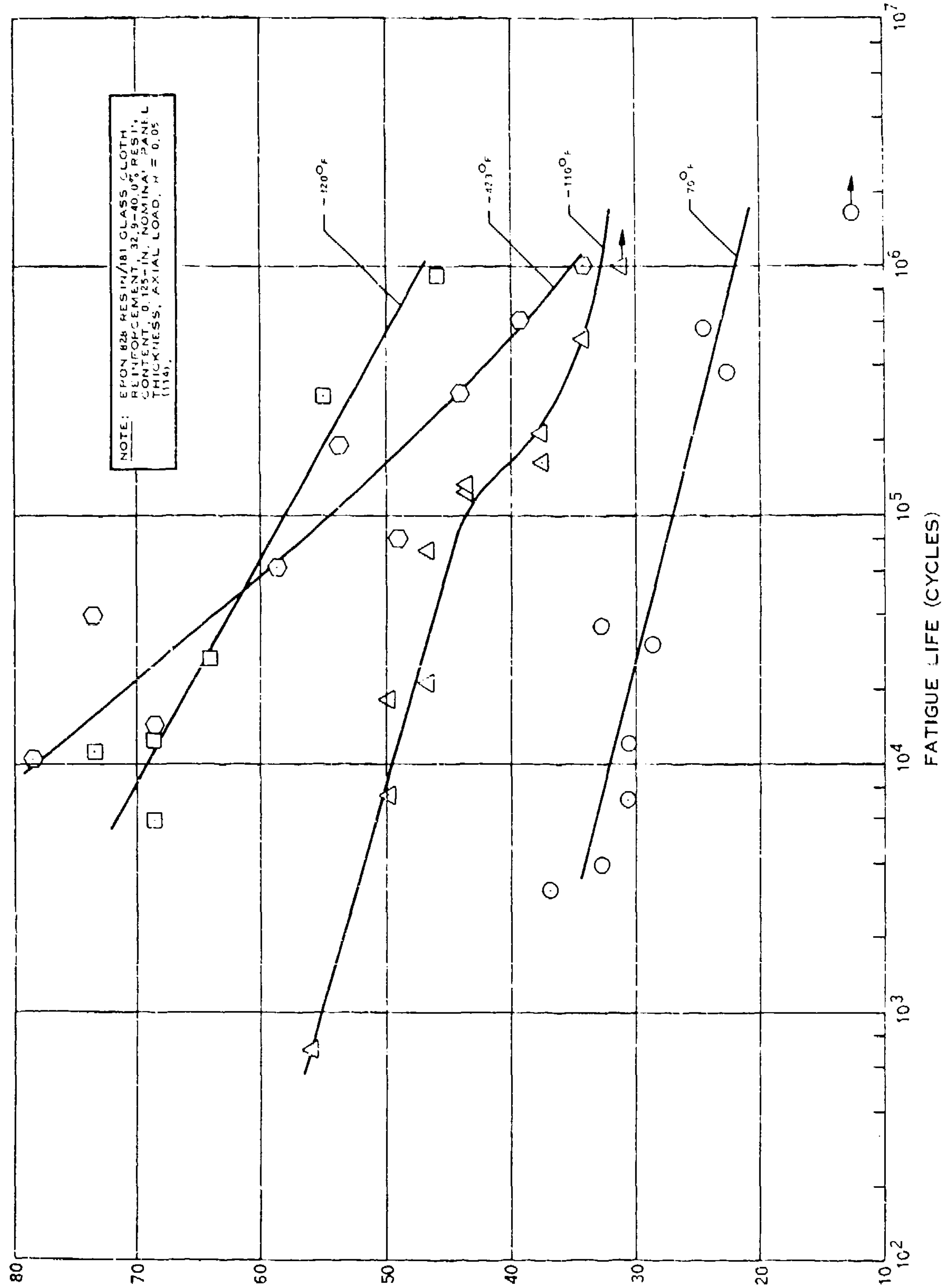
COMPRESSIVE STRENGTH OF EPOXY-FIBERGLAS LAMINATE

(6-68)



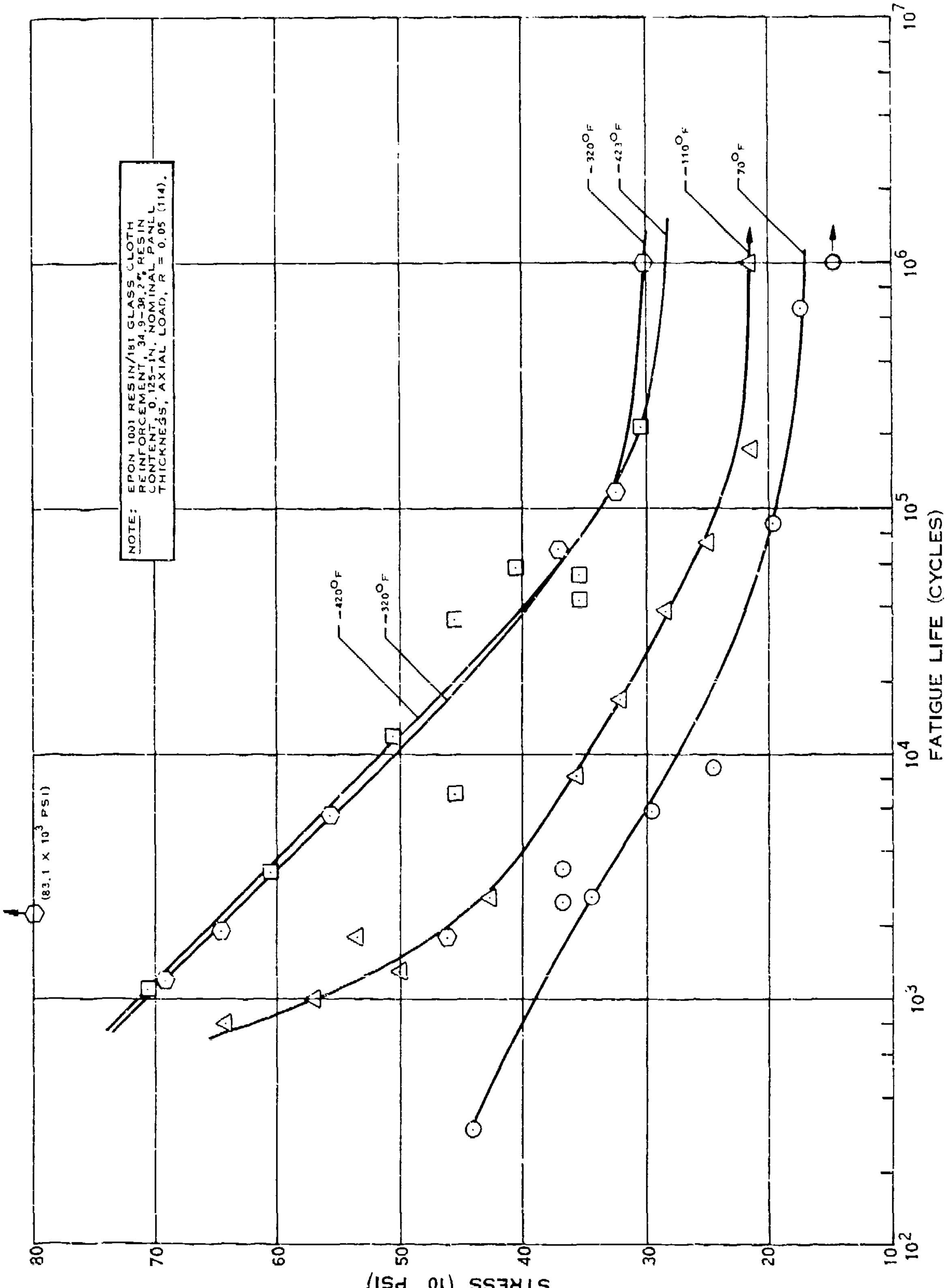
COMPRESSIVE MODULUS OF EPOXY-FIBERGLAS LAMINATE

(1−65)



FATIGUE STRENGTH OF EPOXY-FIBERGLAS LAMINATE

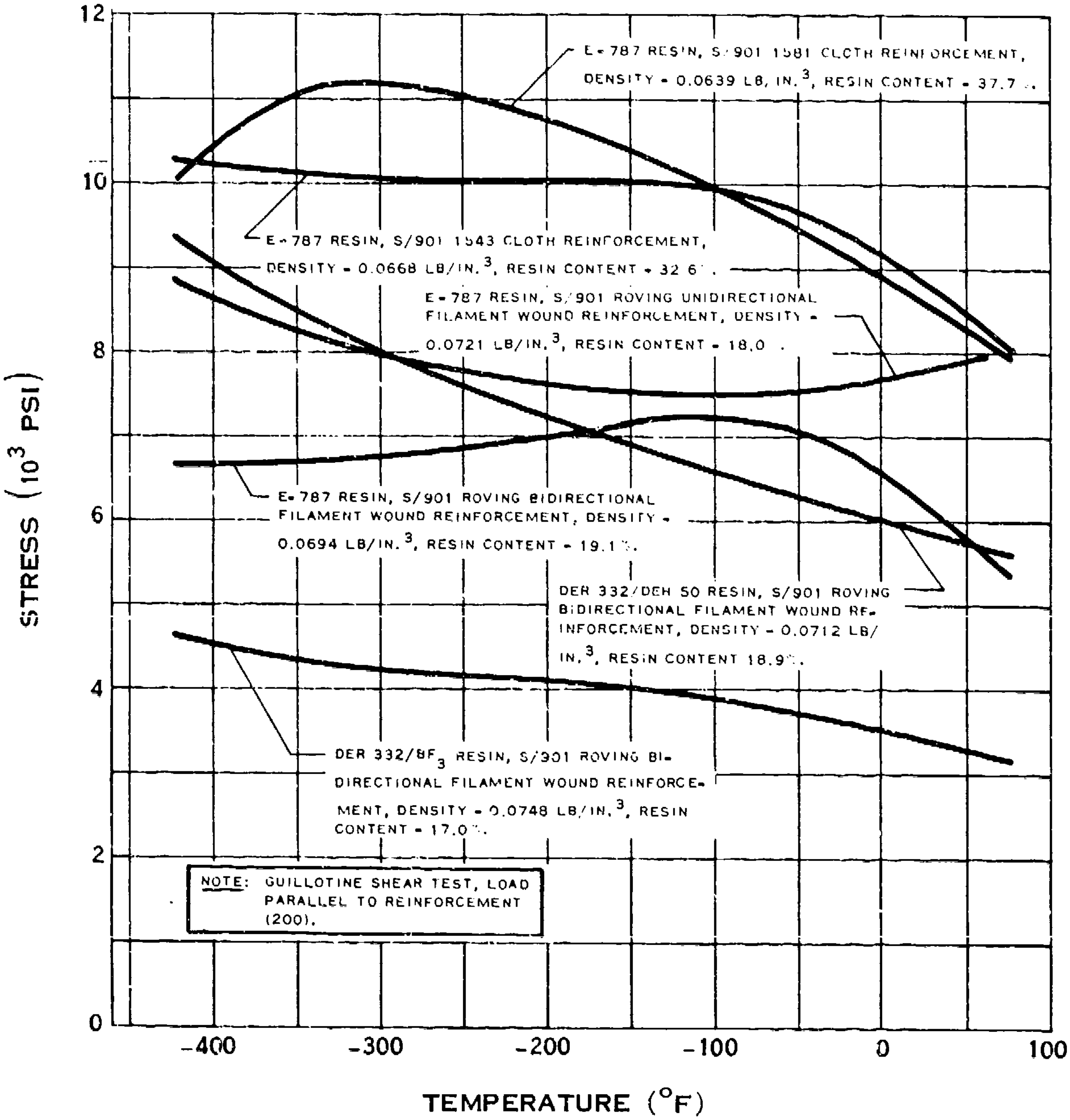
(7-64)



FATIGUE STRENGTH OF EPOXY-FIBERGLAS LAMINATE

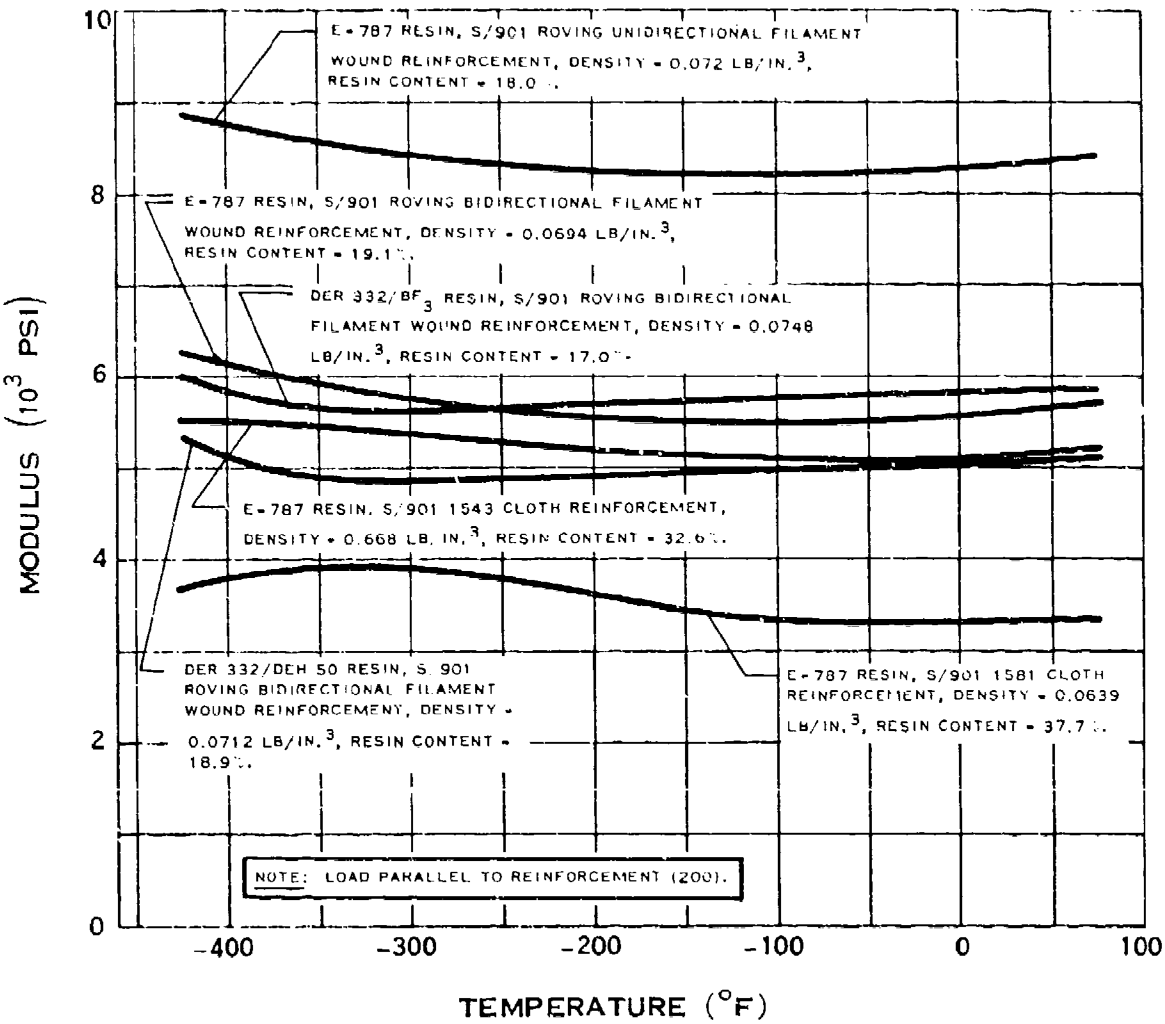
(7-64)

H.1.p



SHEAR STRENGTH OF EPOXY-FIBERGLAS LAMINATE

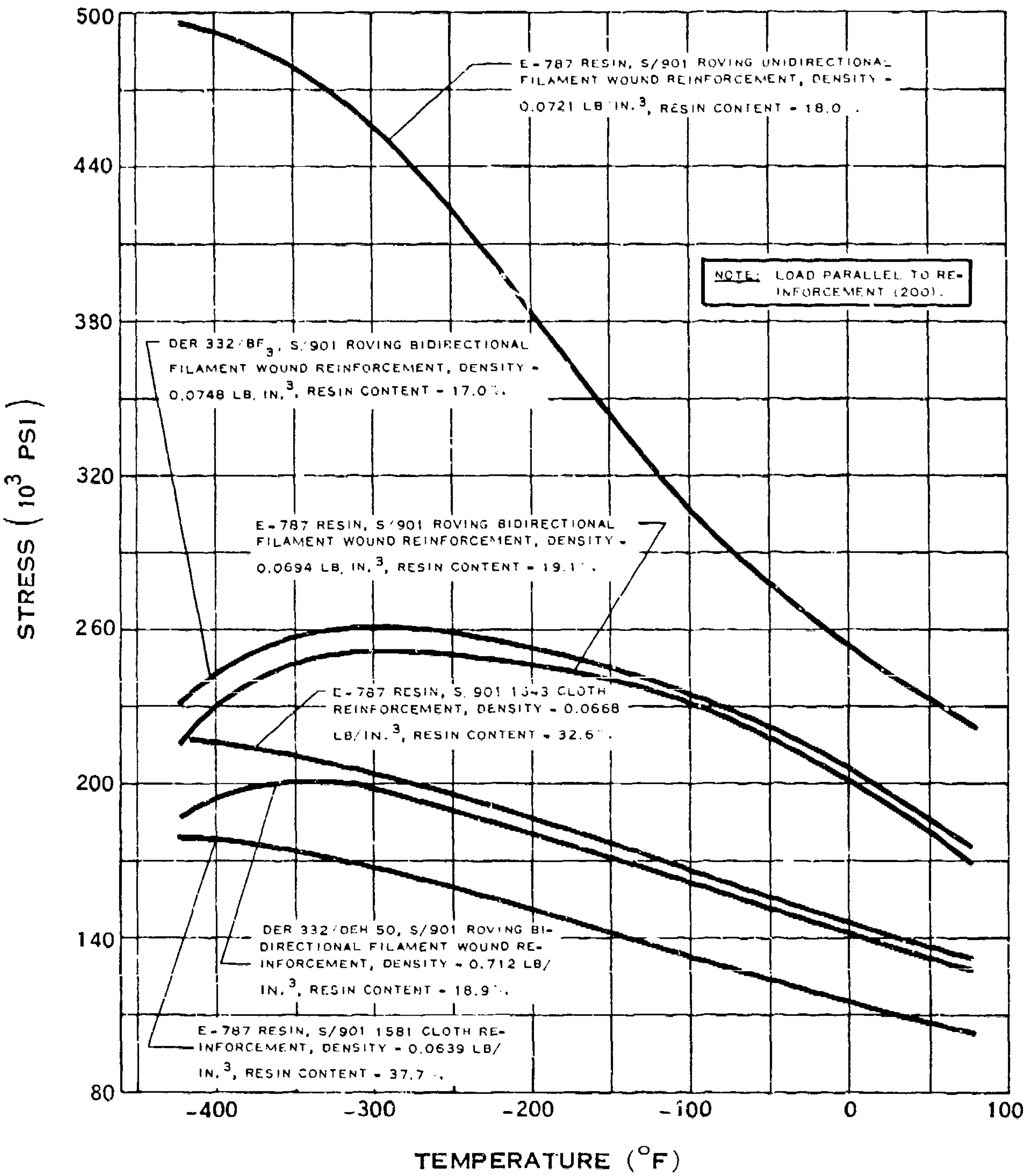
(6-68)



FLEXURAL STRENGTH OF EPOXY-FIBERGLAS LAMINATE

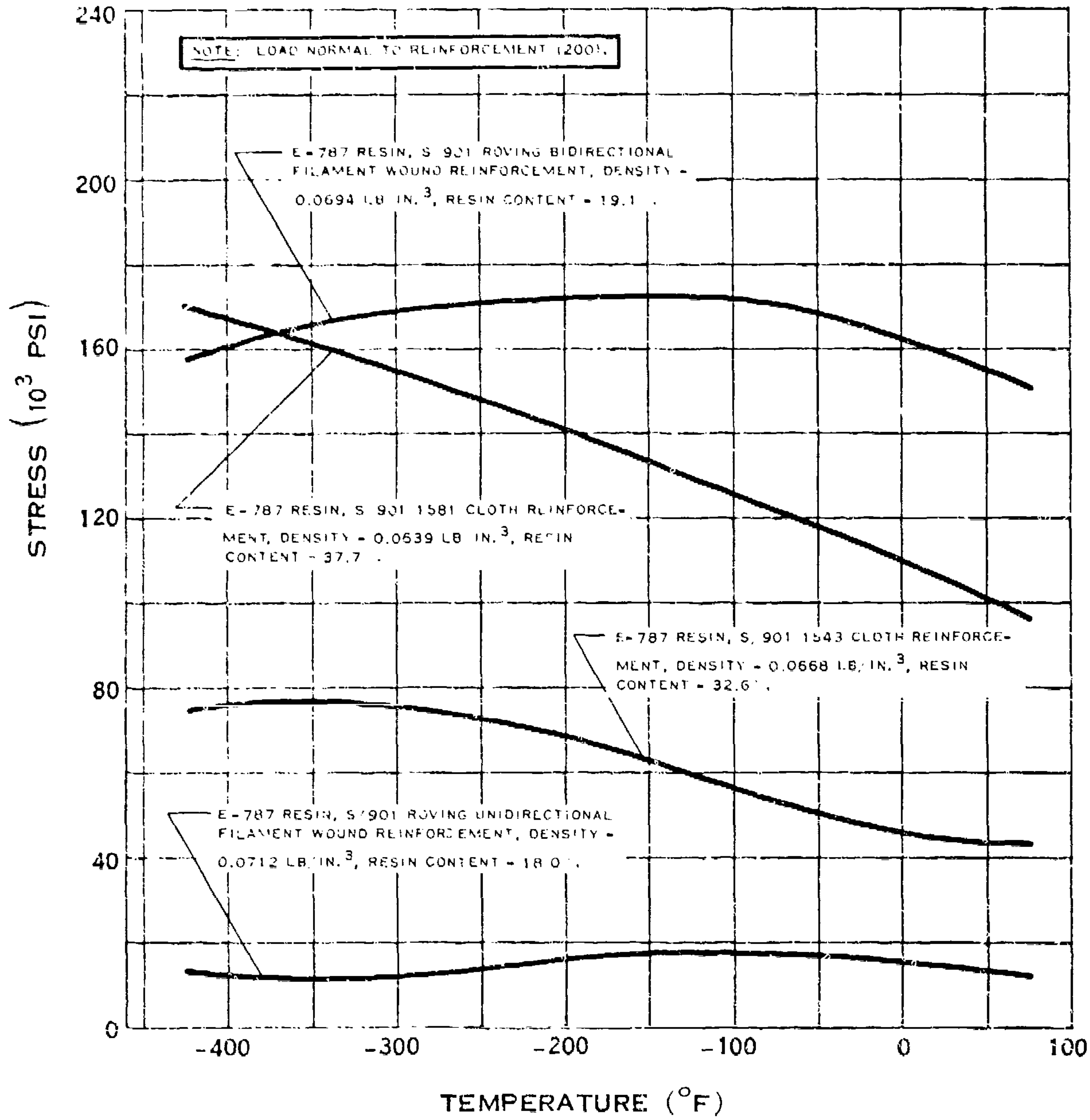
(6-68)

H.1.r-1



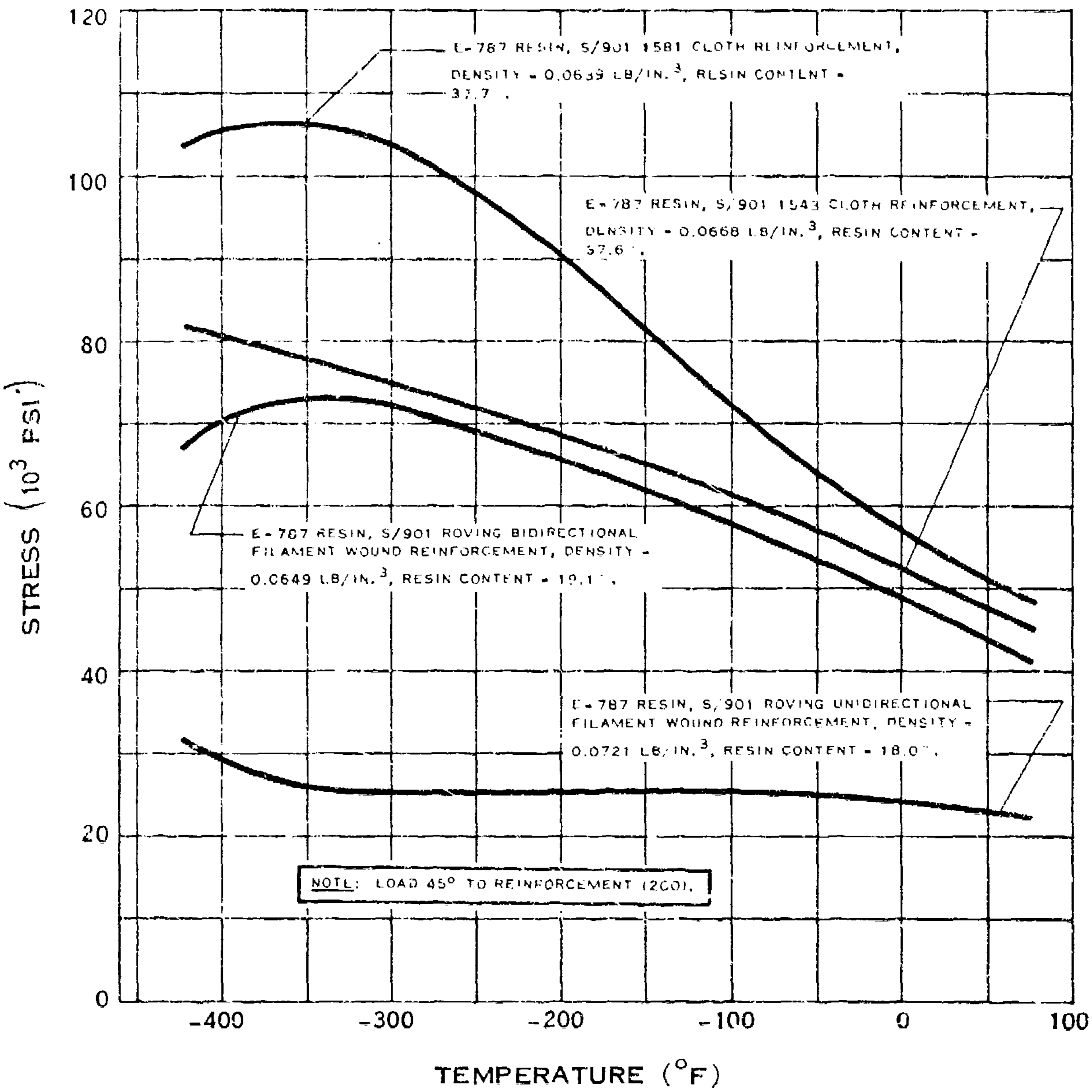
FLEXURAL STRENGTH OF EPOXY-FIBERGLAS LAMINATE

(6-68)



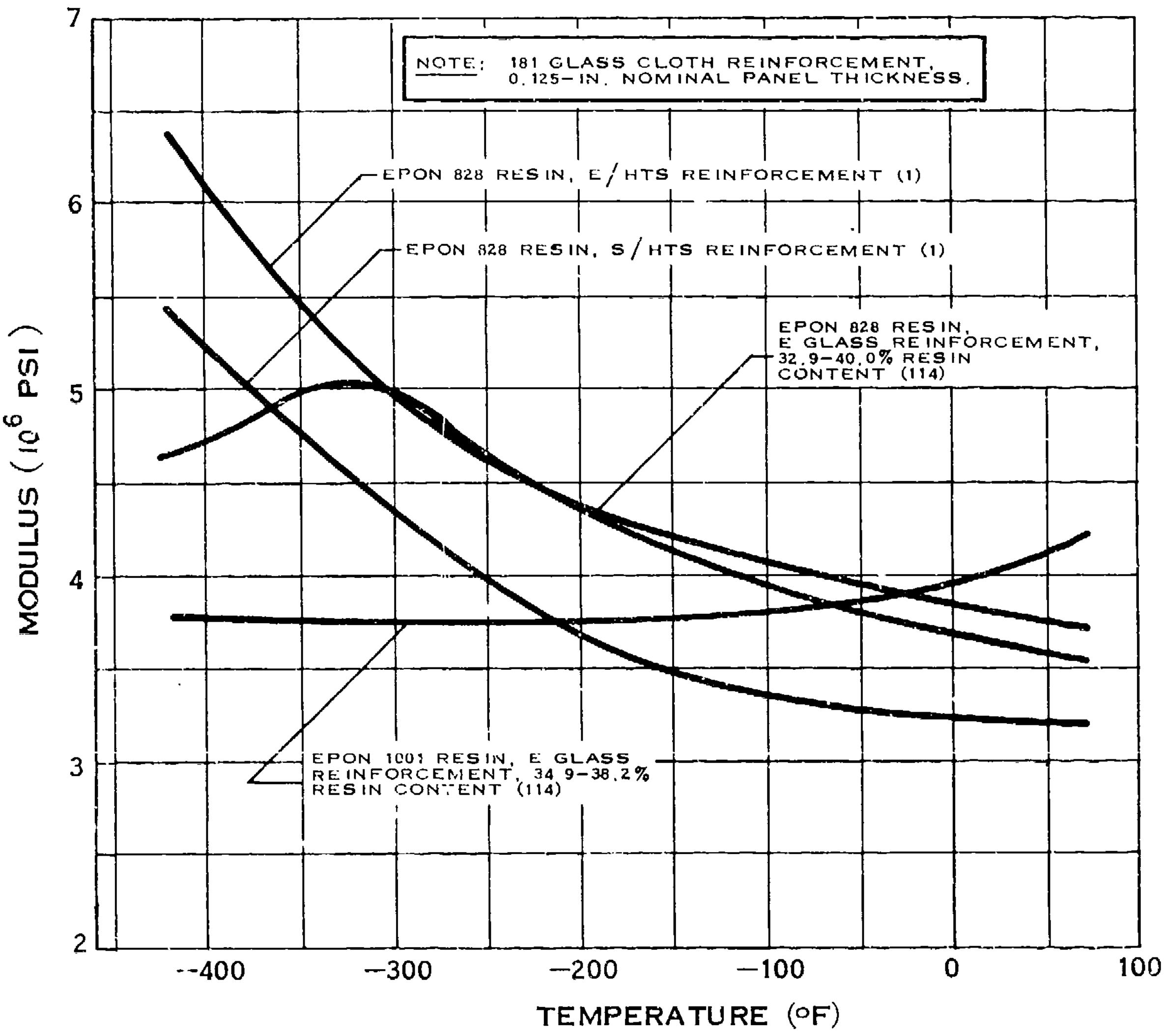
FLEXURAL STRENGTH OF EPOXY-FIBERGLAS LAMINATE

(6-68)



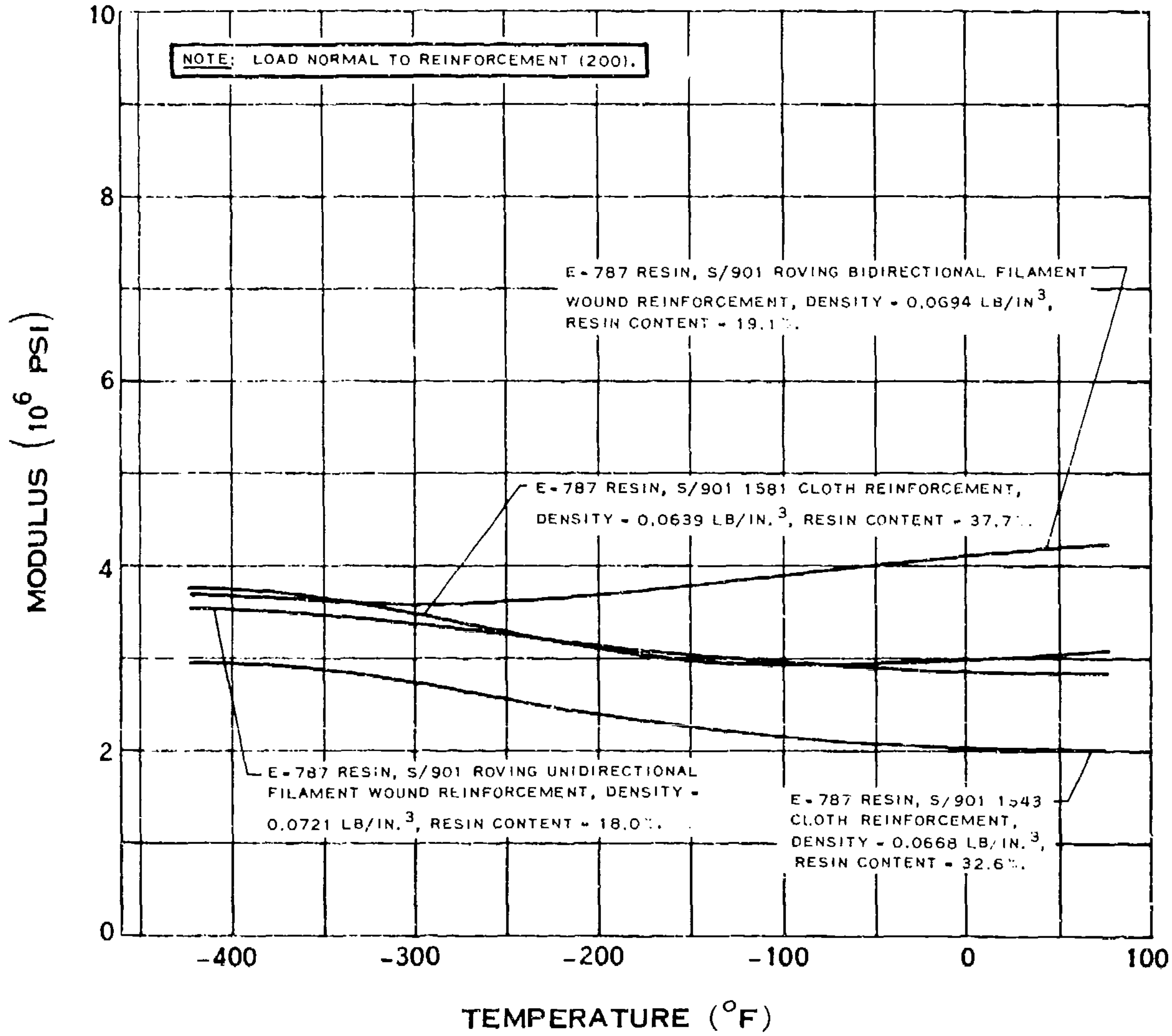
FLEXURAL STRENGTH OF EPOXY-FIBERGLAS LAMINATE

(6-68)



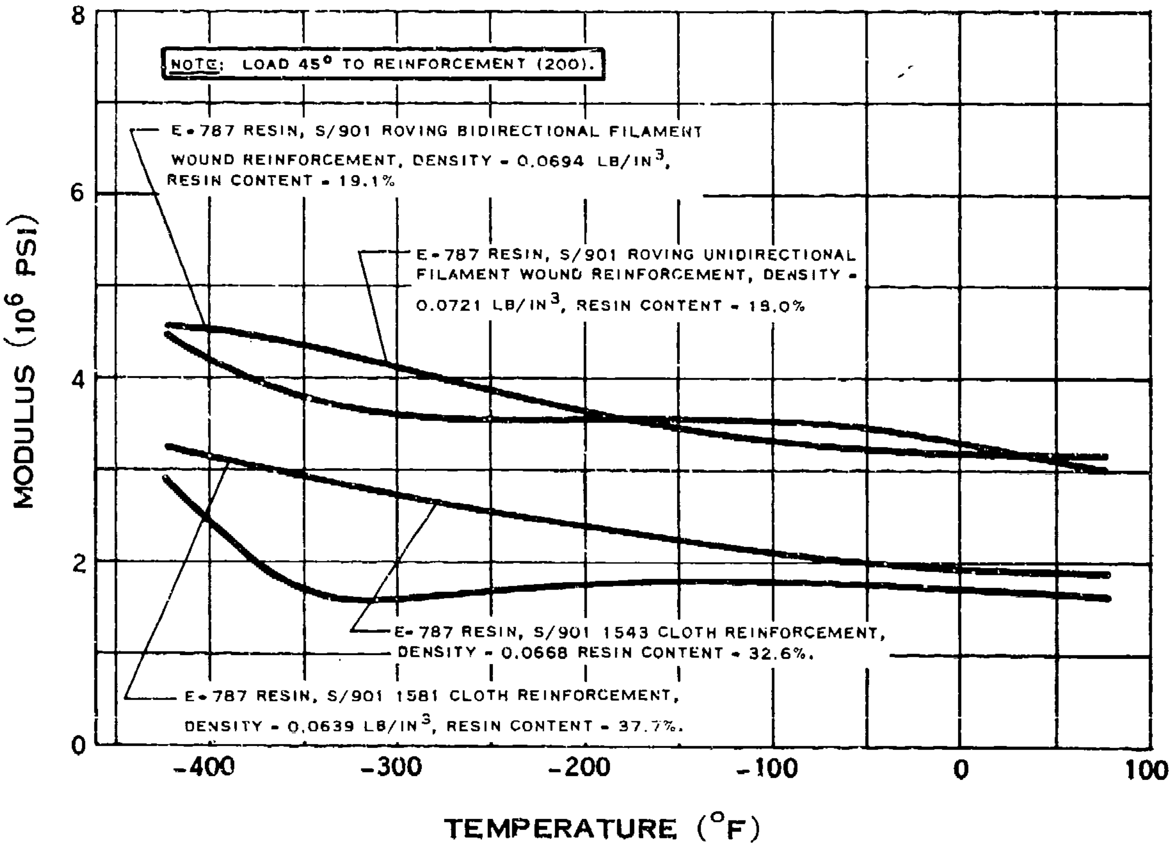
FLEXURAL MODULUS OF EPOXY-FIBERGLAS LAMINATE

(1-65)



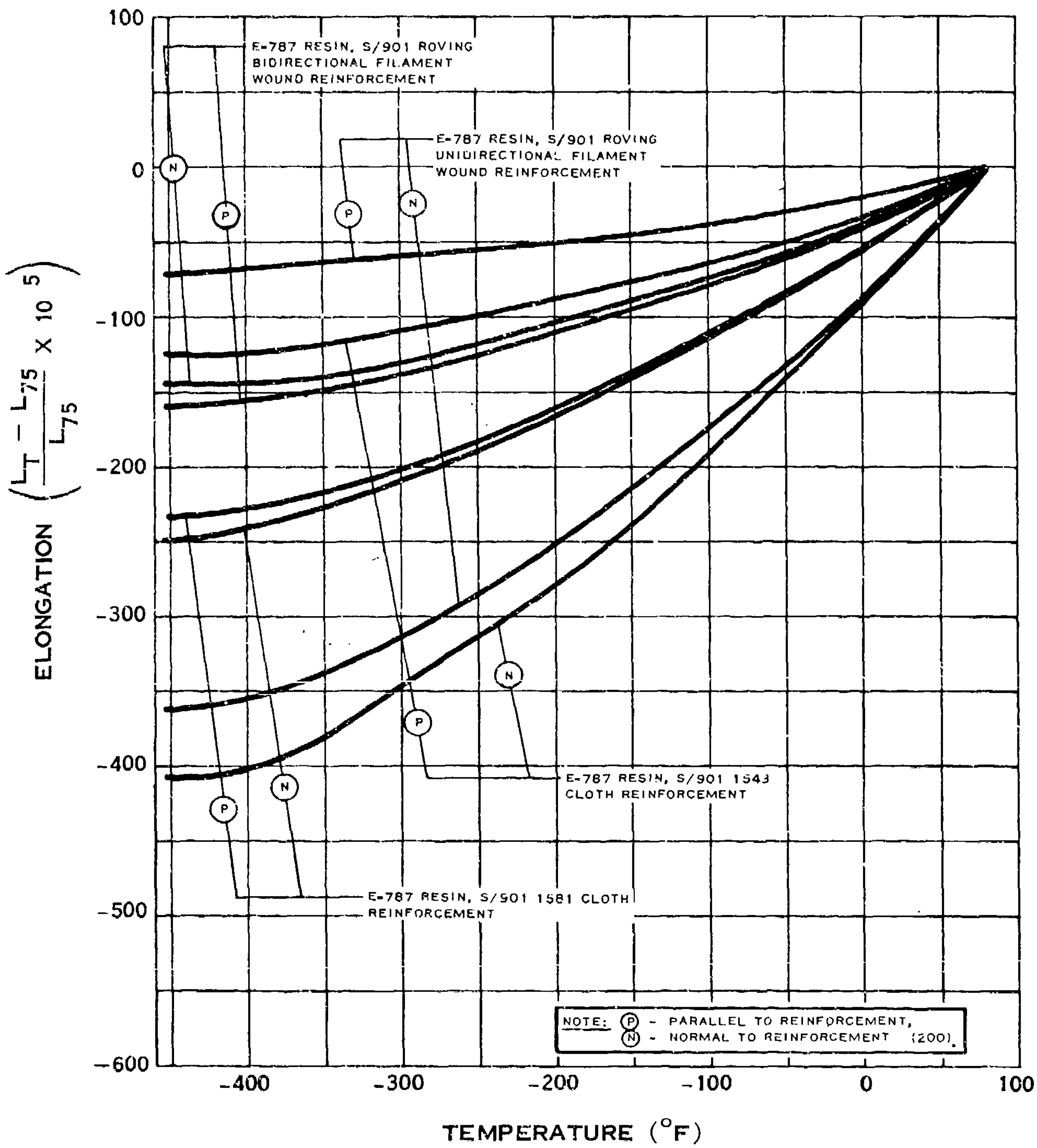
FLEXURAL MODULUS OF EPOXY-FIBERGLAS LAMINATE

(6-68)



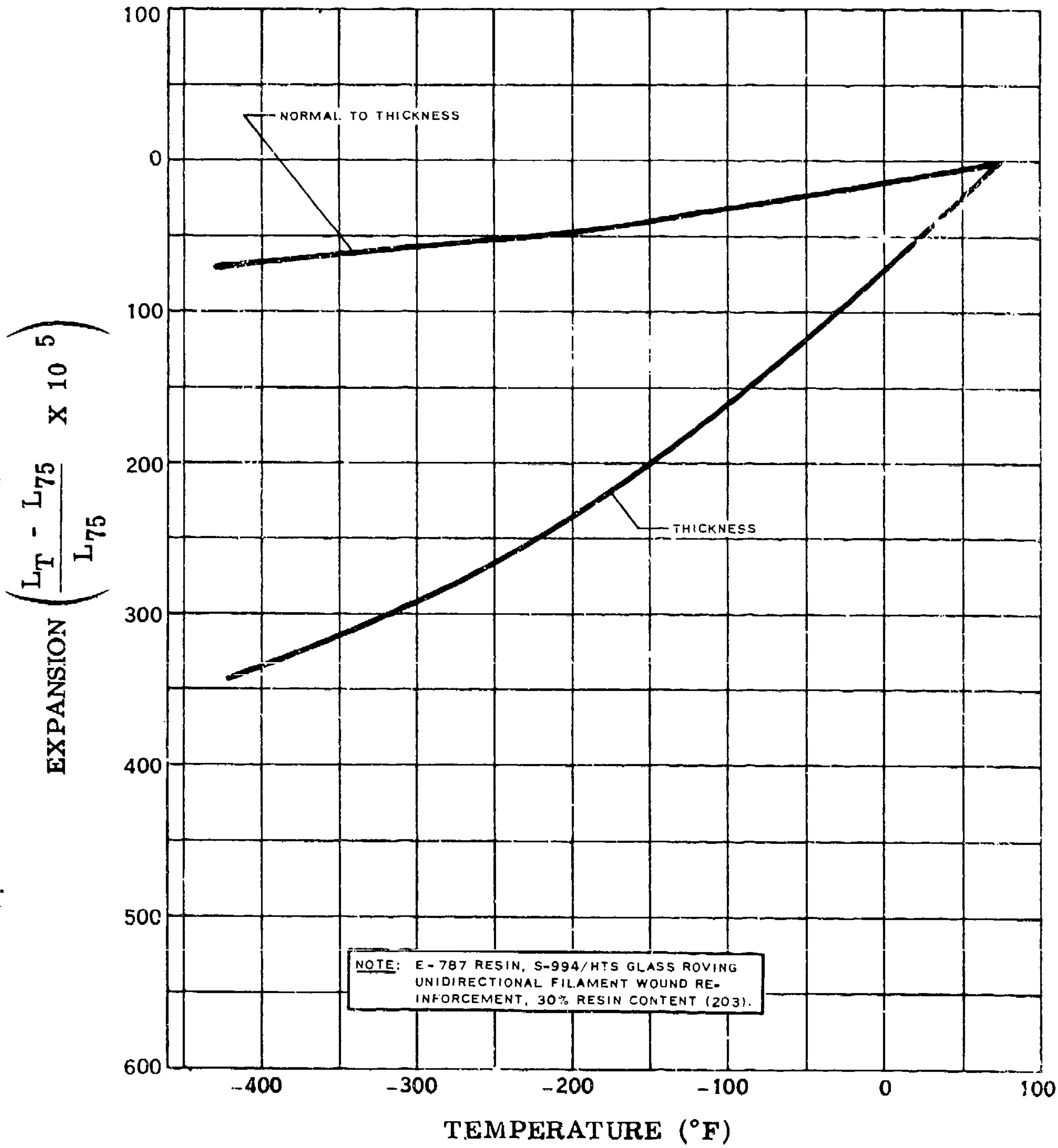
FLEXURAL MODULUS OF EPOXY-FIBERGLAS LAMINATE

(6-68)



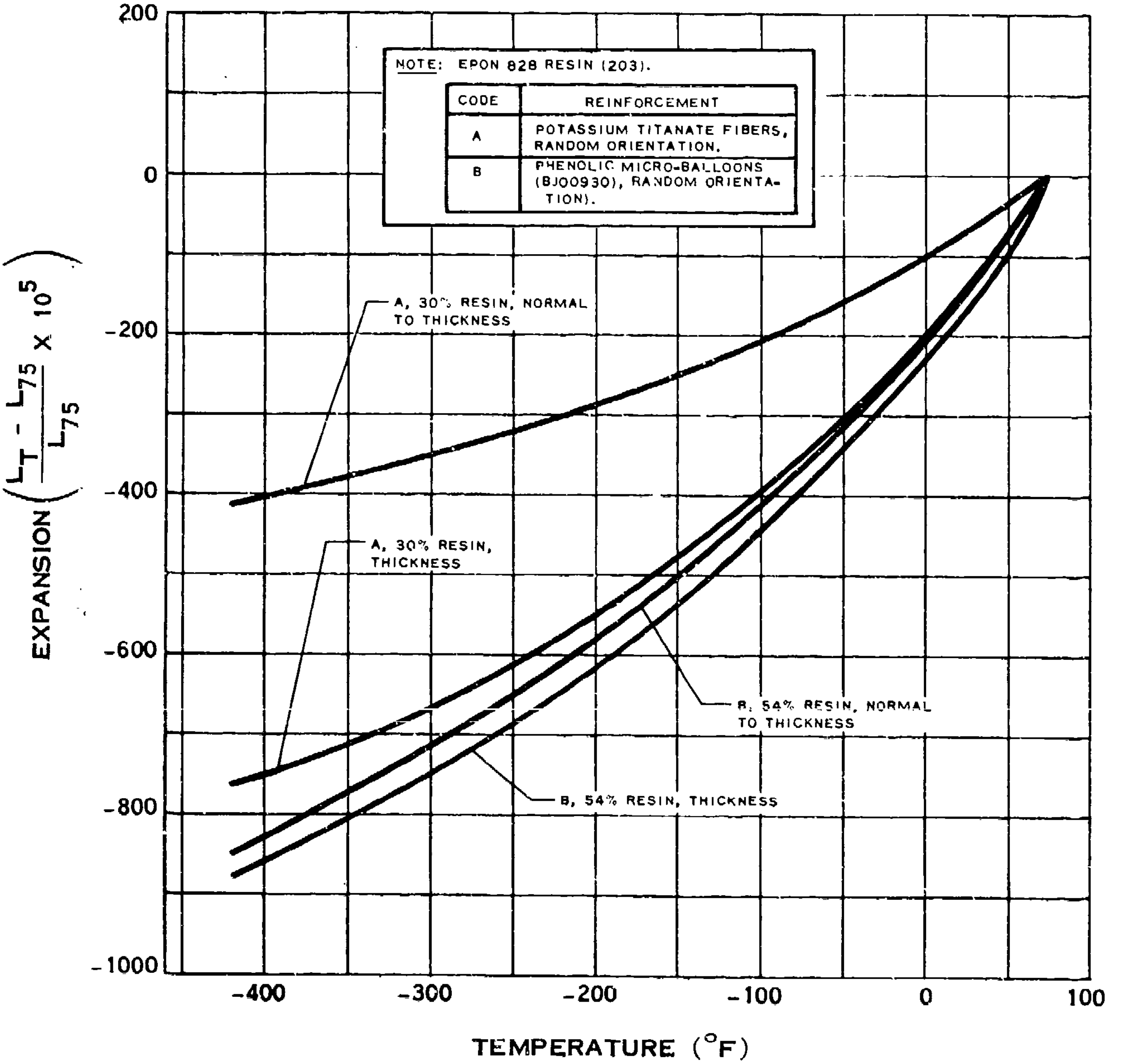
THERMAL EXPANSION OF EPOXY-FIBERGLAS LAMINATE

(6-68)



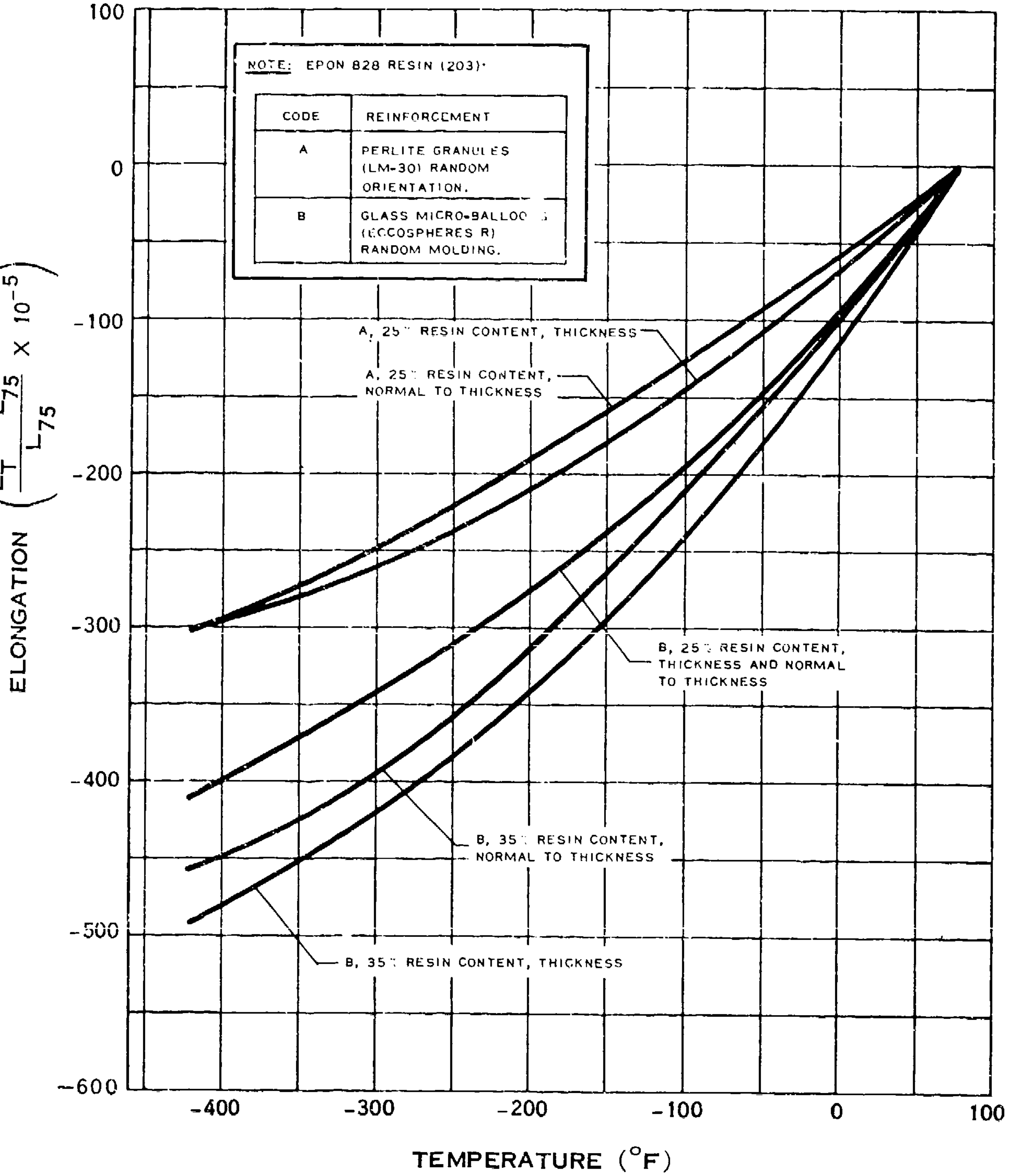
THERMAL EXPANSION OF EPOXY-FIBERGLAS LAMINATE

(6-68)



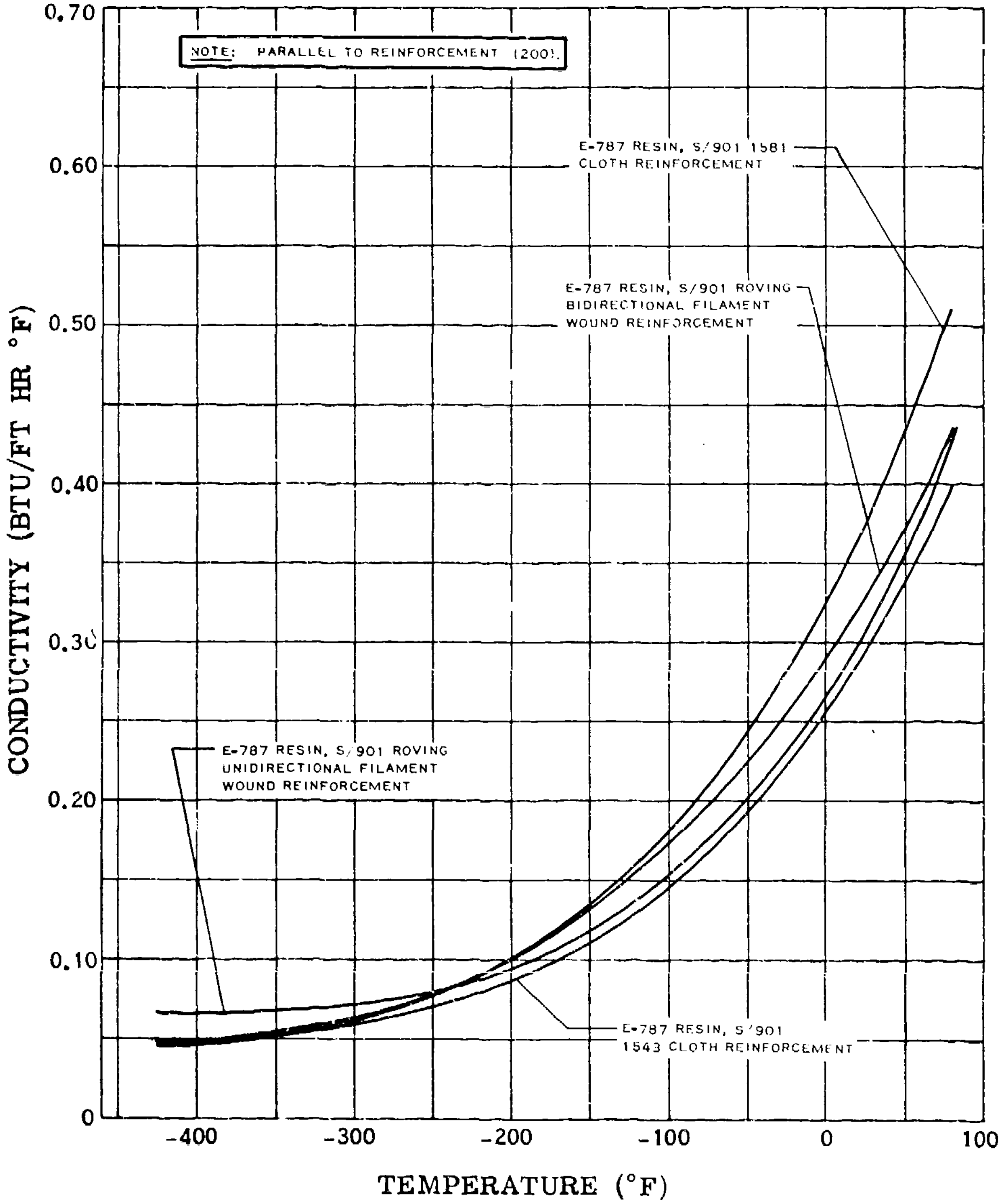
THERMAL EXPANSION OF REINFORCED MOLDED EPOXY

(6-68)



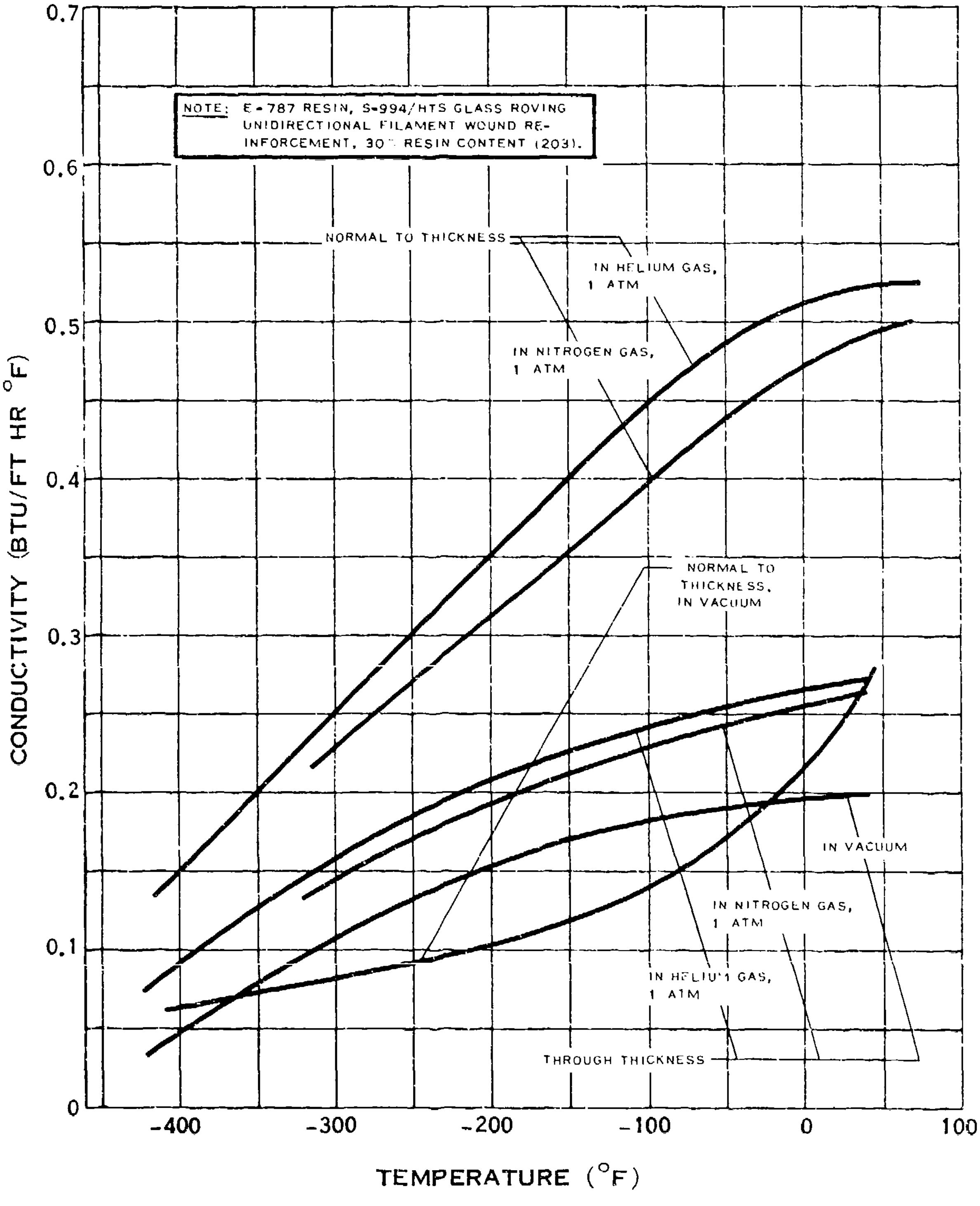
THERMAL EXPANSION OF REINFORCED MOLDED EPOXY

(6-68)



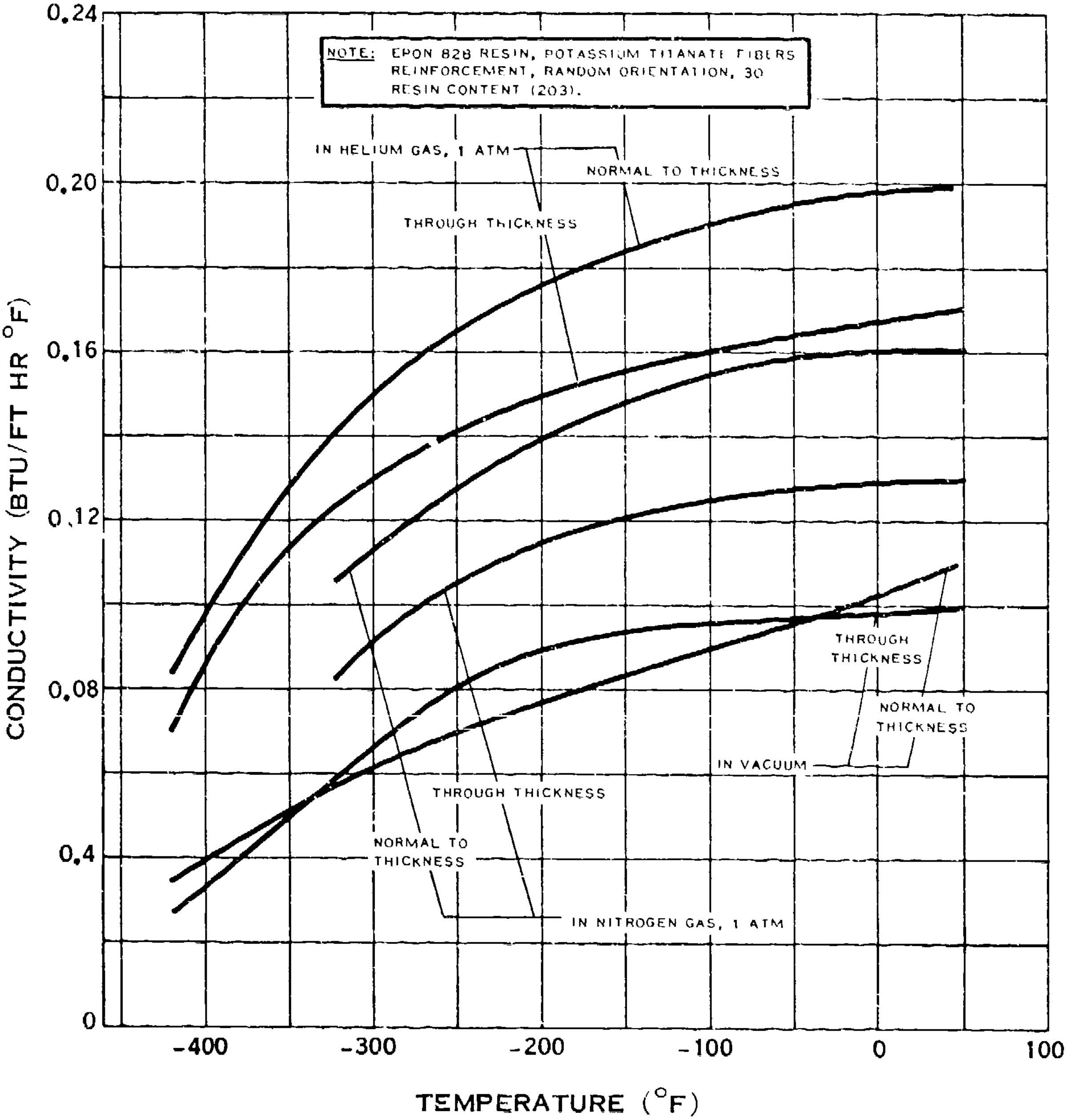
THERMAL CONDUCTIVITY OF EPOXY-FIBERGLAS LAMINATE

(6-68)



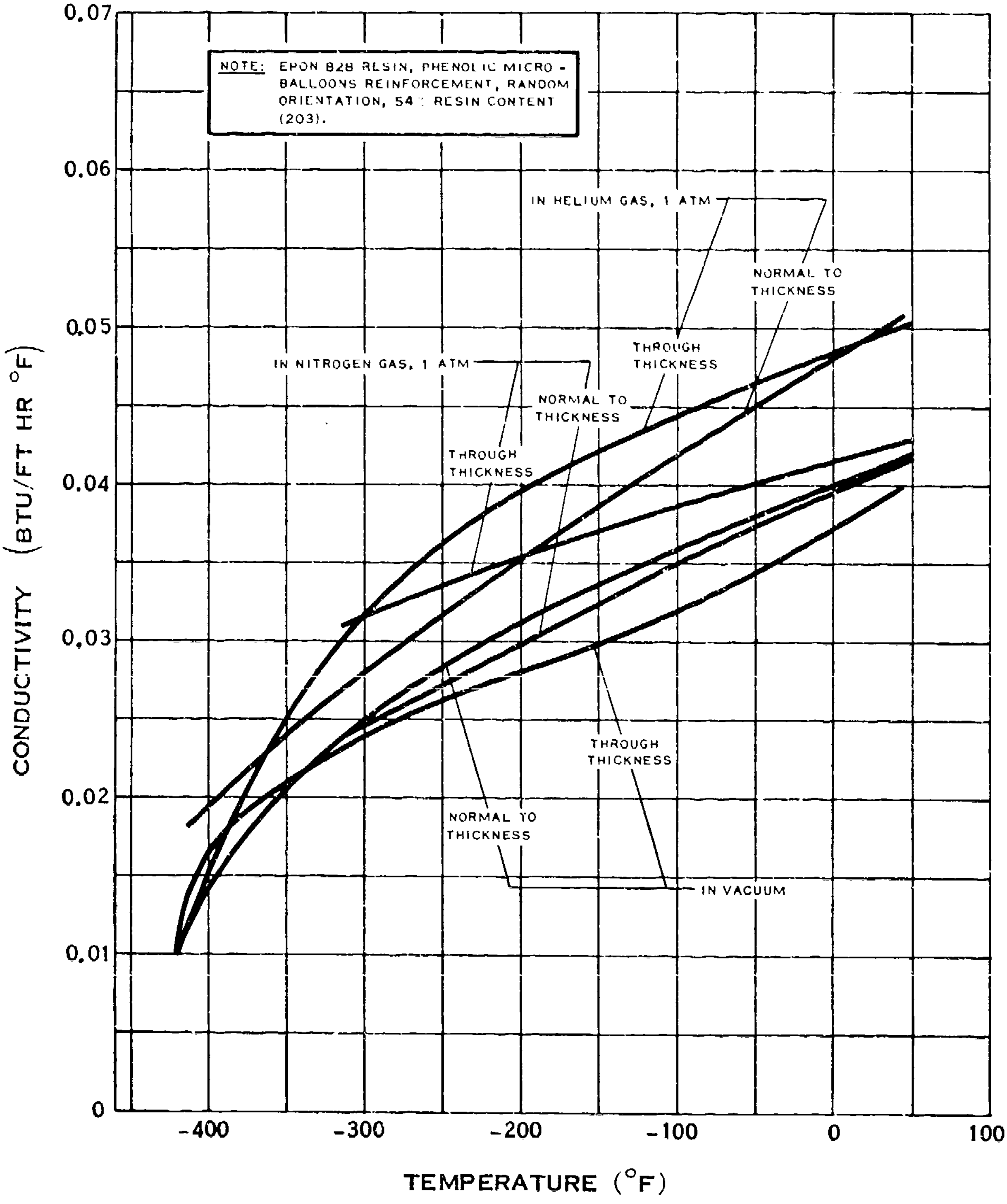
THERMAL CONDUCTIVITY OF EPOXY-FIBERGLAS LAMINATE

(6-68)



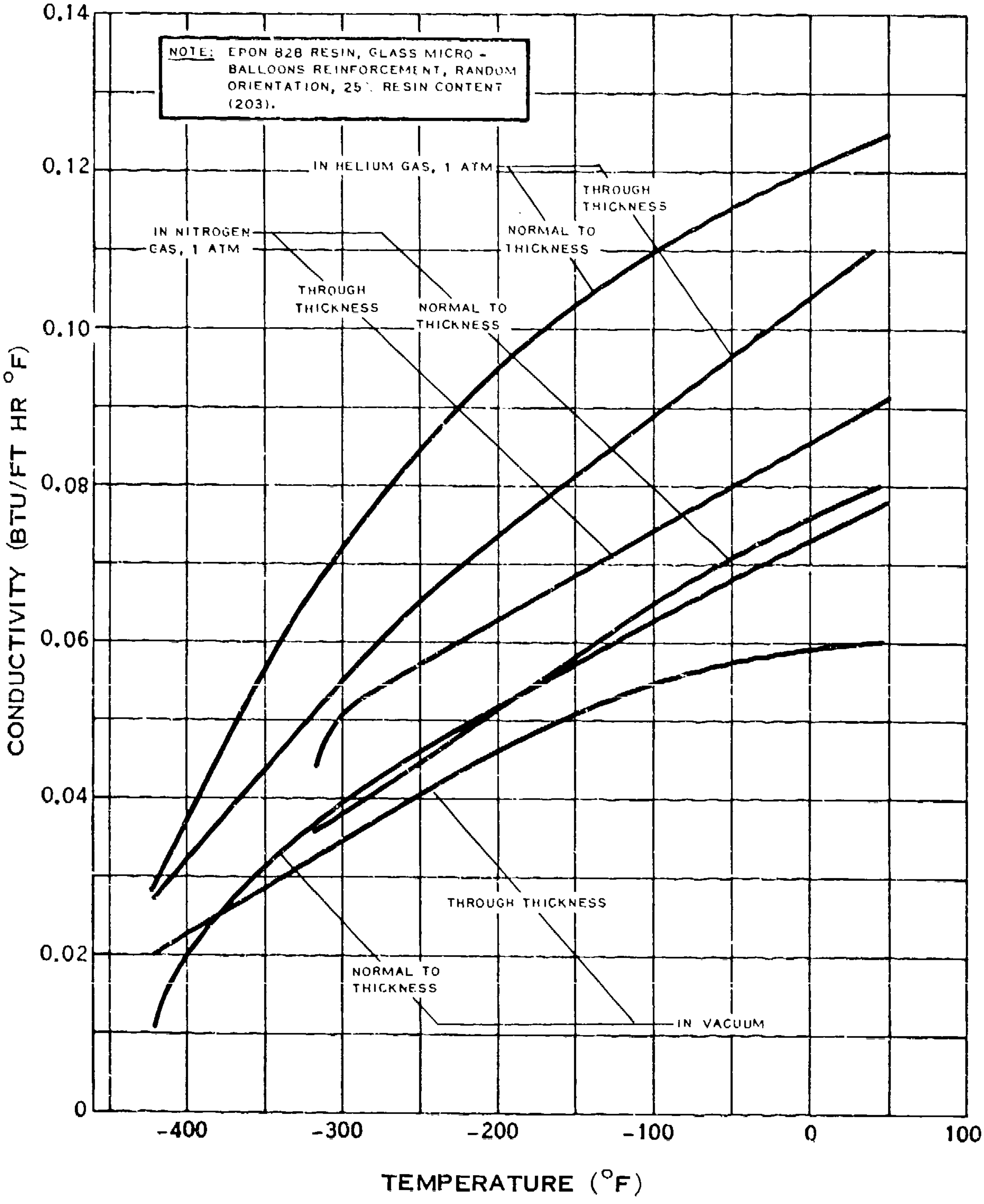
THERMAL CONDUCTIVITY OF REINFORCED MOLDED EPOXY

(6-68)



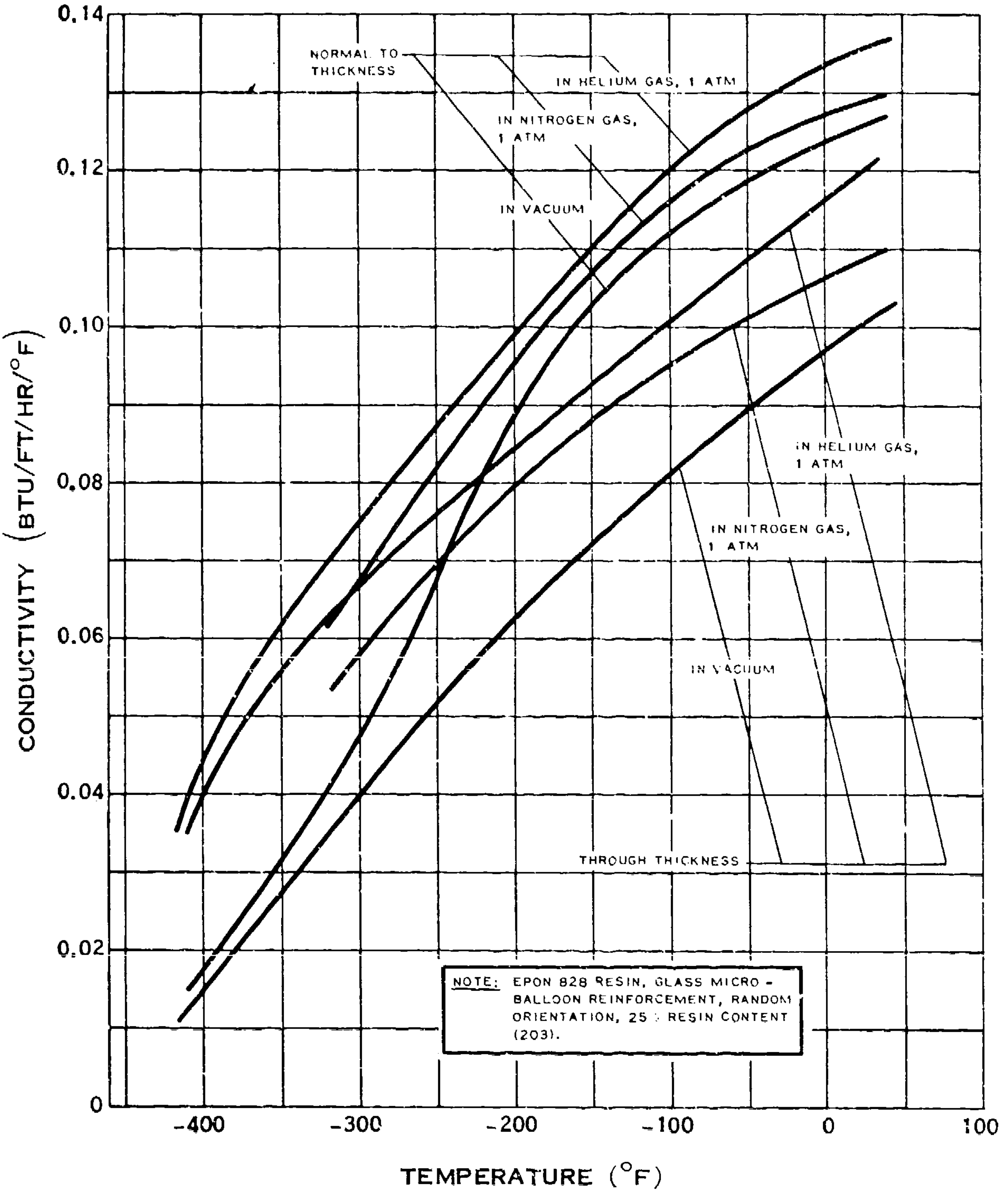
THERMAL CONDUCTIVITY OF REINFORCED MOLDED EPOXY

(6-68)



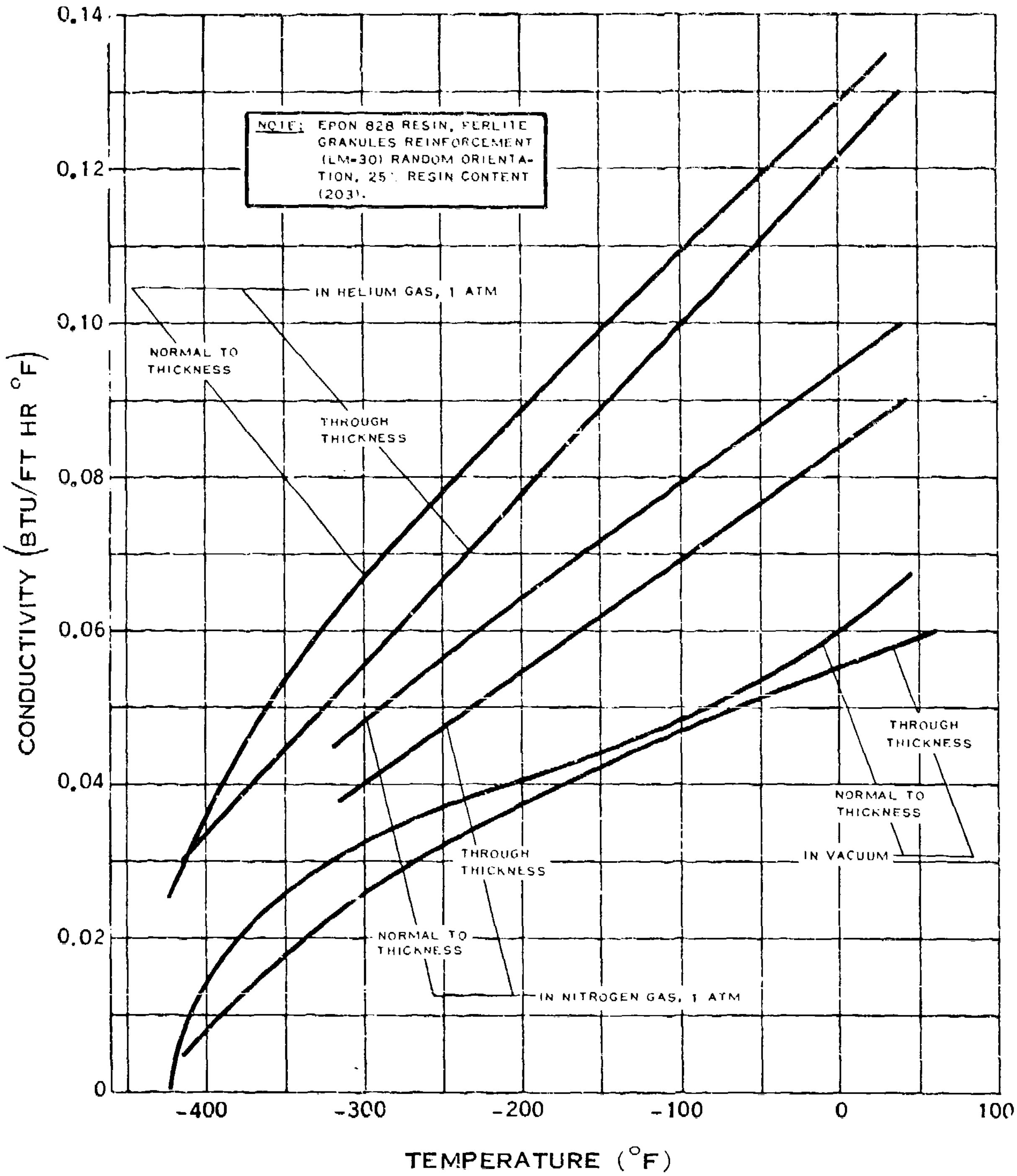
THERMAL CONDUCTIVITY OF REINFORCED MOLDED EPOXY

(6-68)



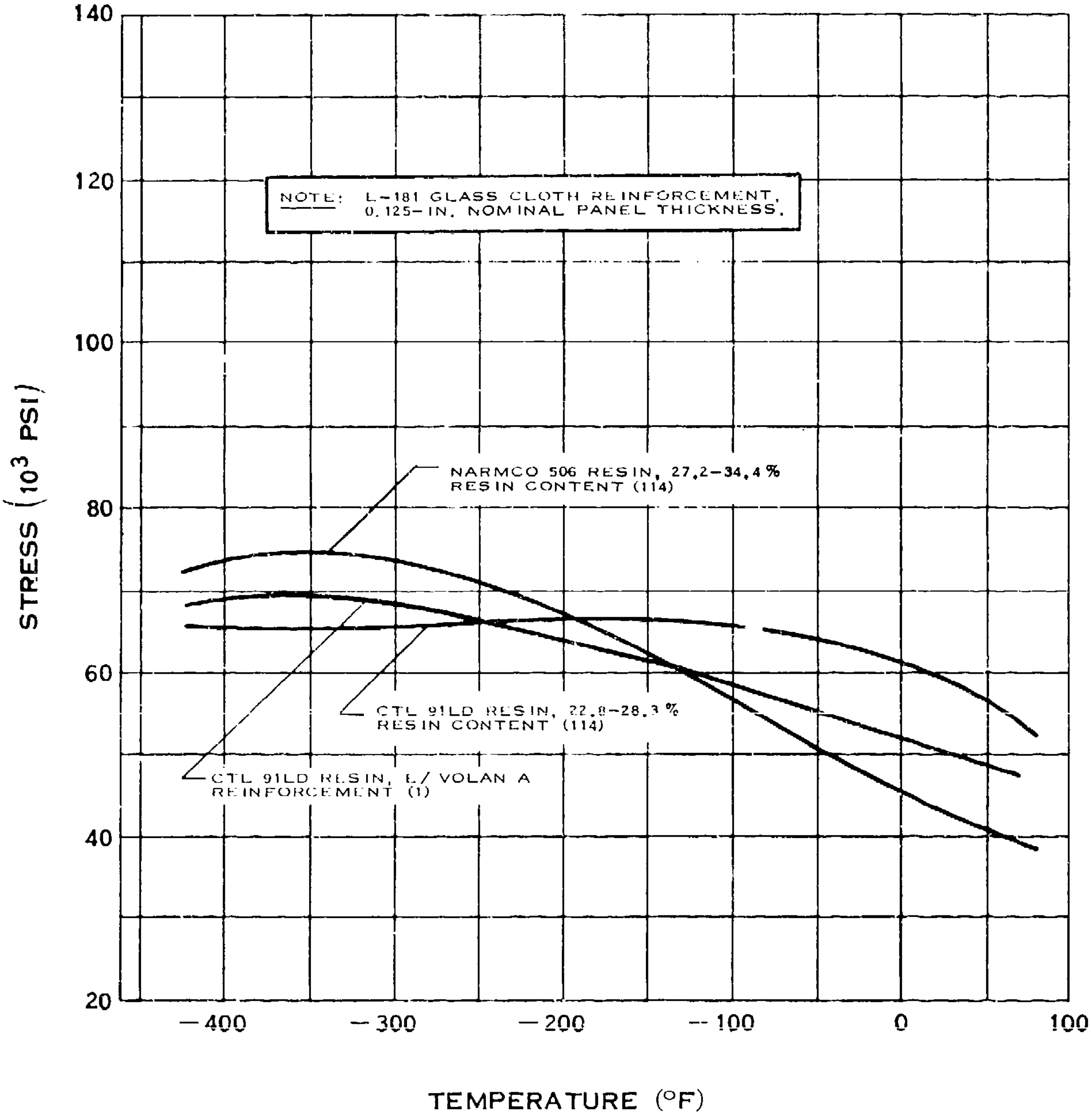
THERMAL CONDUCTIVITY OF REINFORCED MOLDED EPOXY

(6-68)



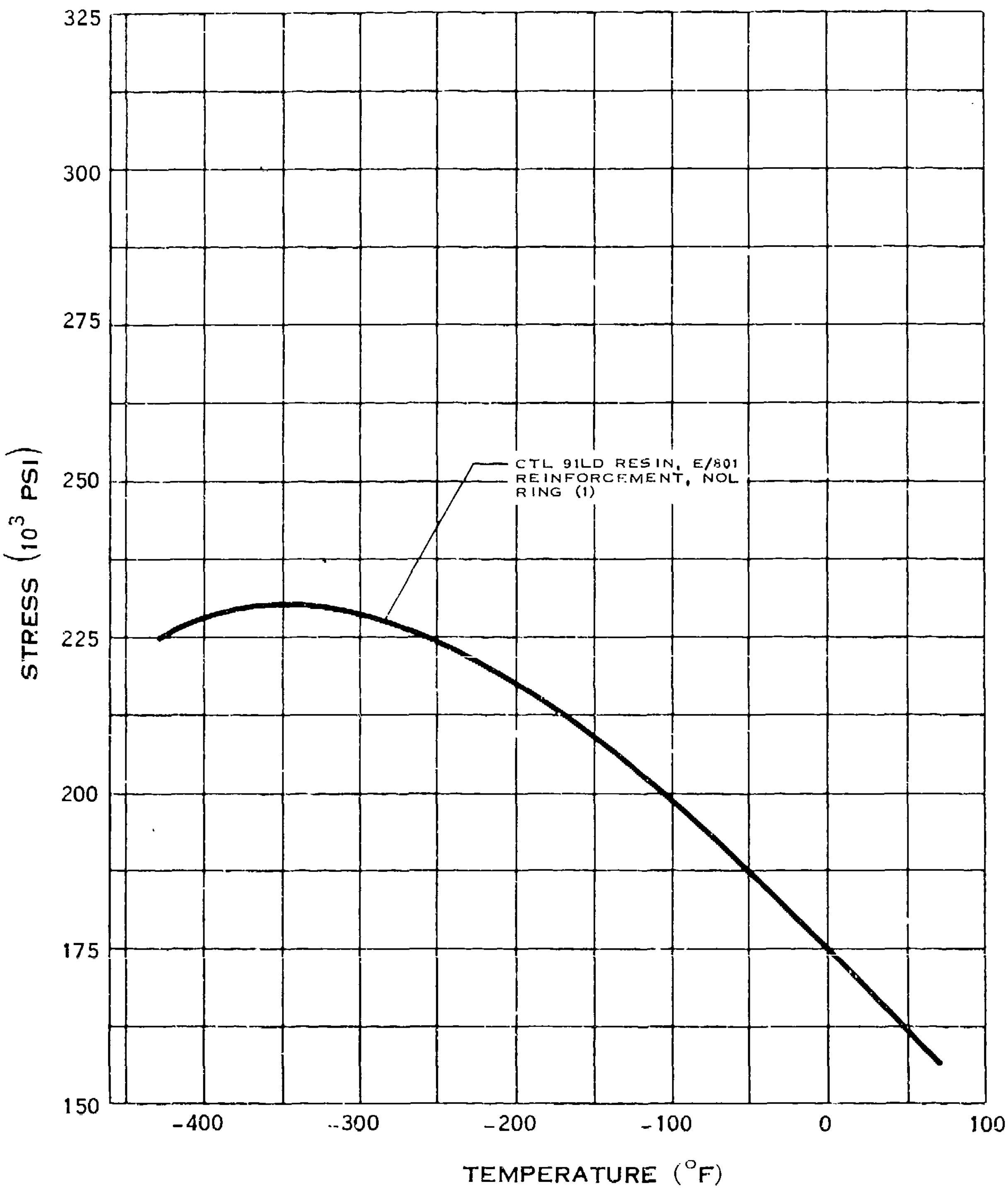
THERMAL CONDUCTIVITY OF REINFORCED MOLDED EPOXY

(6-68)



TENSILE STRENGTH OF PHENOLIC - FIBERGLAS LAMINATE

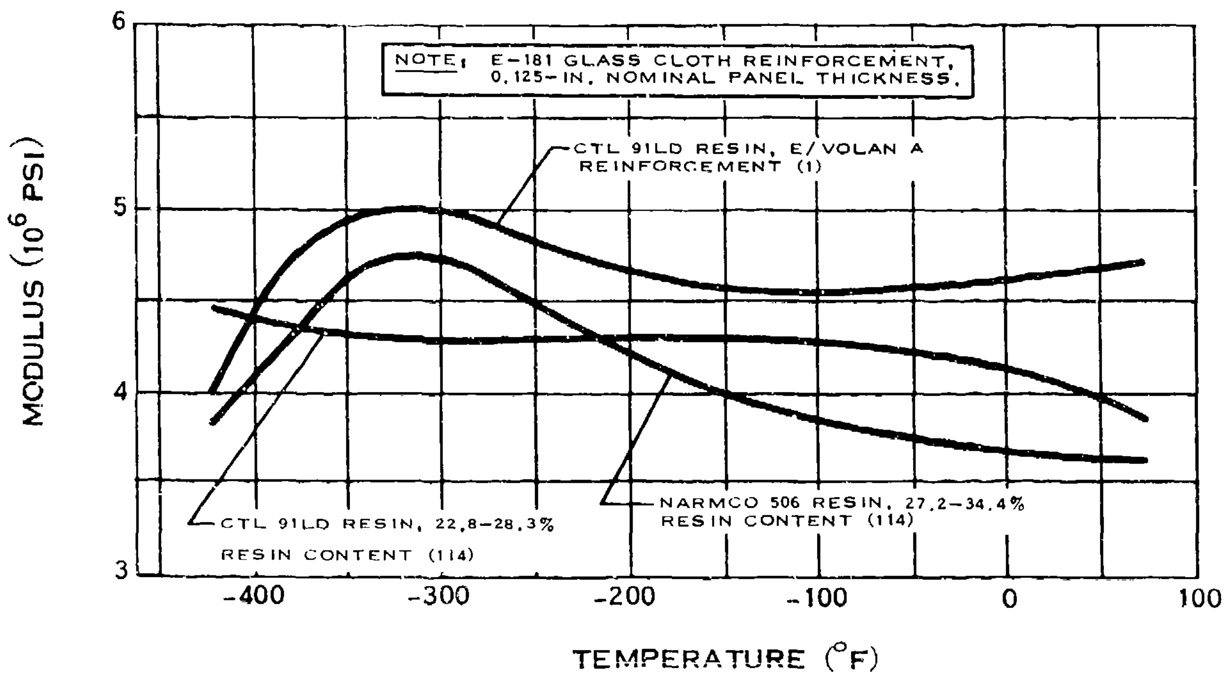
(1-65)



TENSILE STRENGTH OF PHENOLIC-FIBERGLAS FILAMENT WOUND RINGS

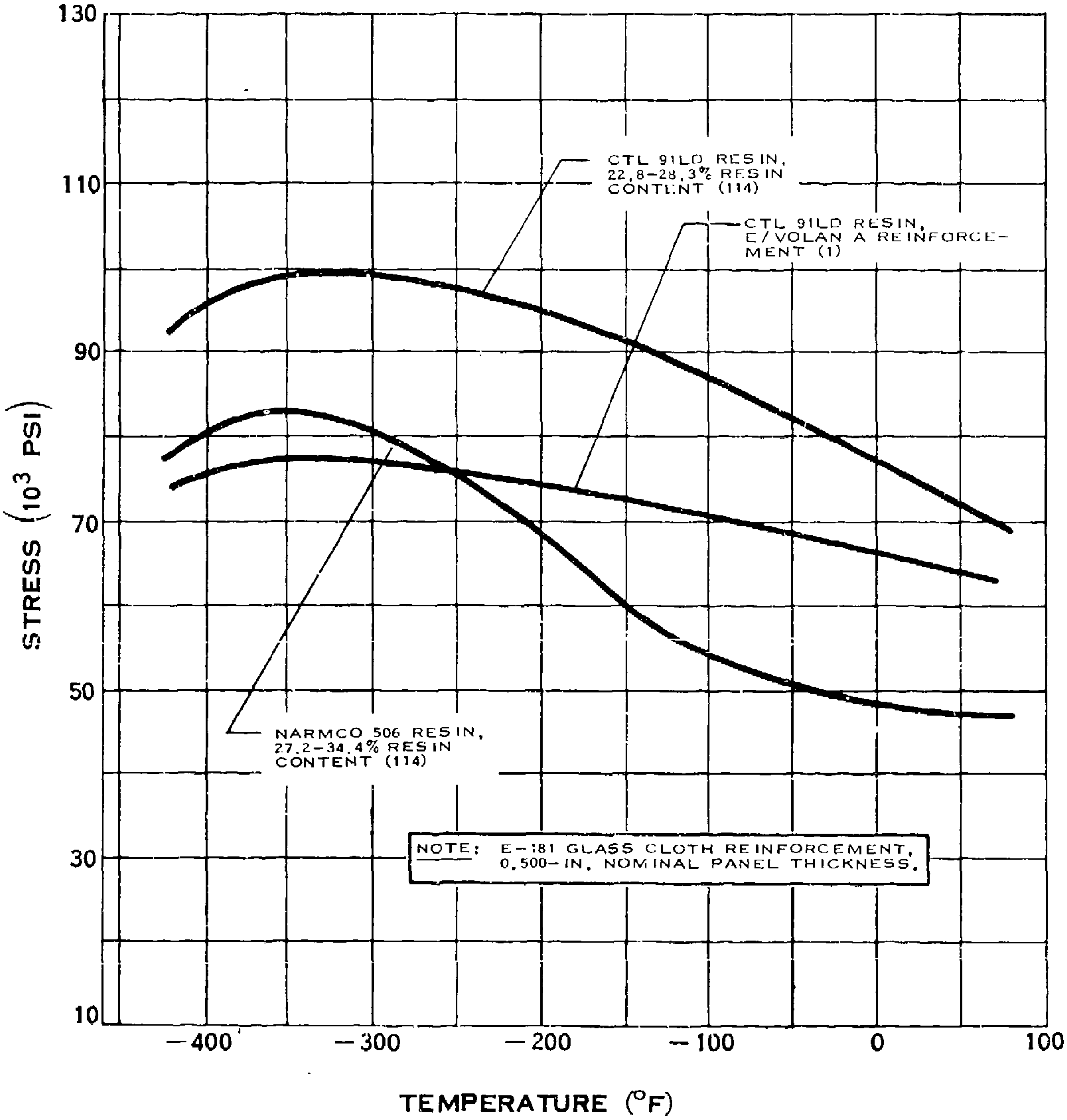
(1-65)

H.2.i



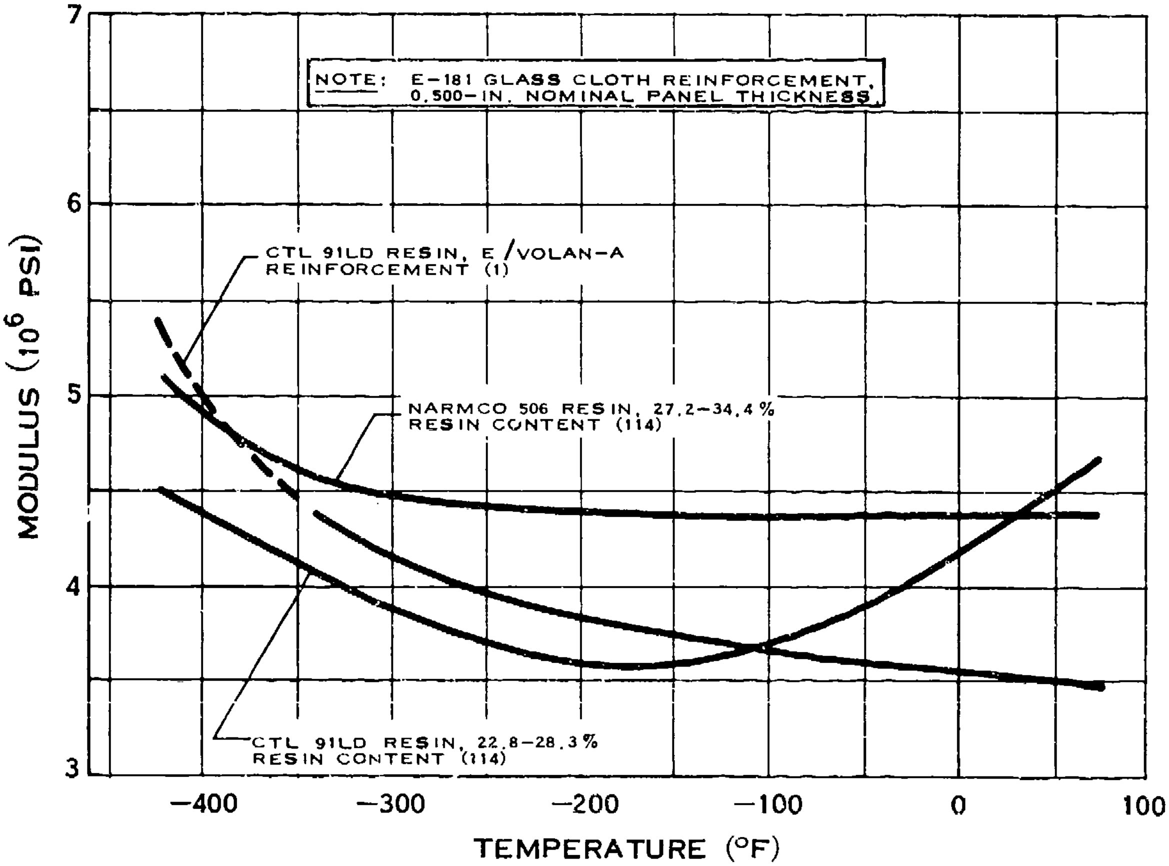
MODULUS OF ELASTICITY OF PHENOLIC-FIBERGLAS LAMINATE

(1-65)



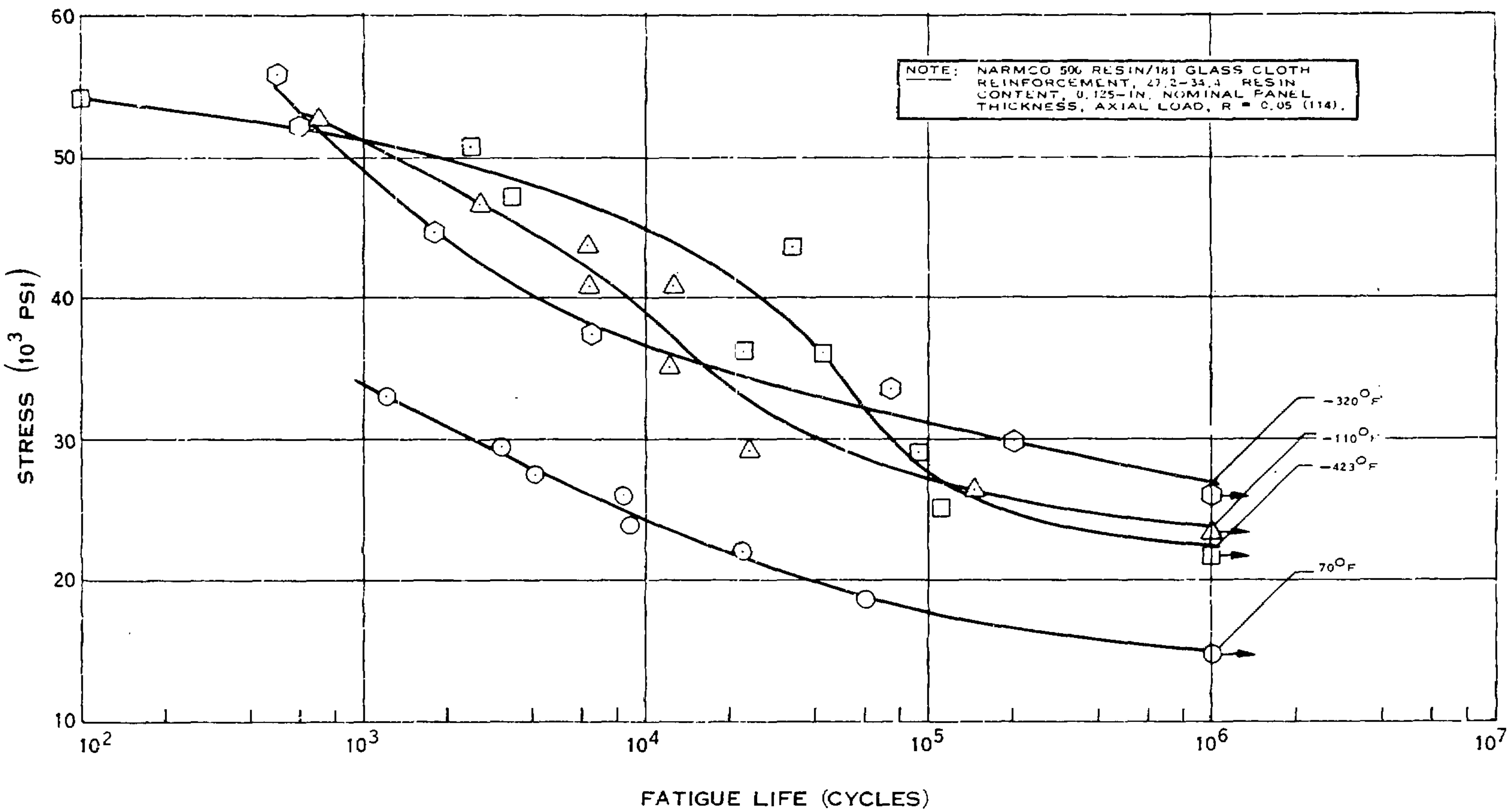
COMPRESSIVE STRENGTH OF PHENOLIC - FIBERGLAS LAMINATE

(1-65)

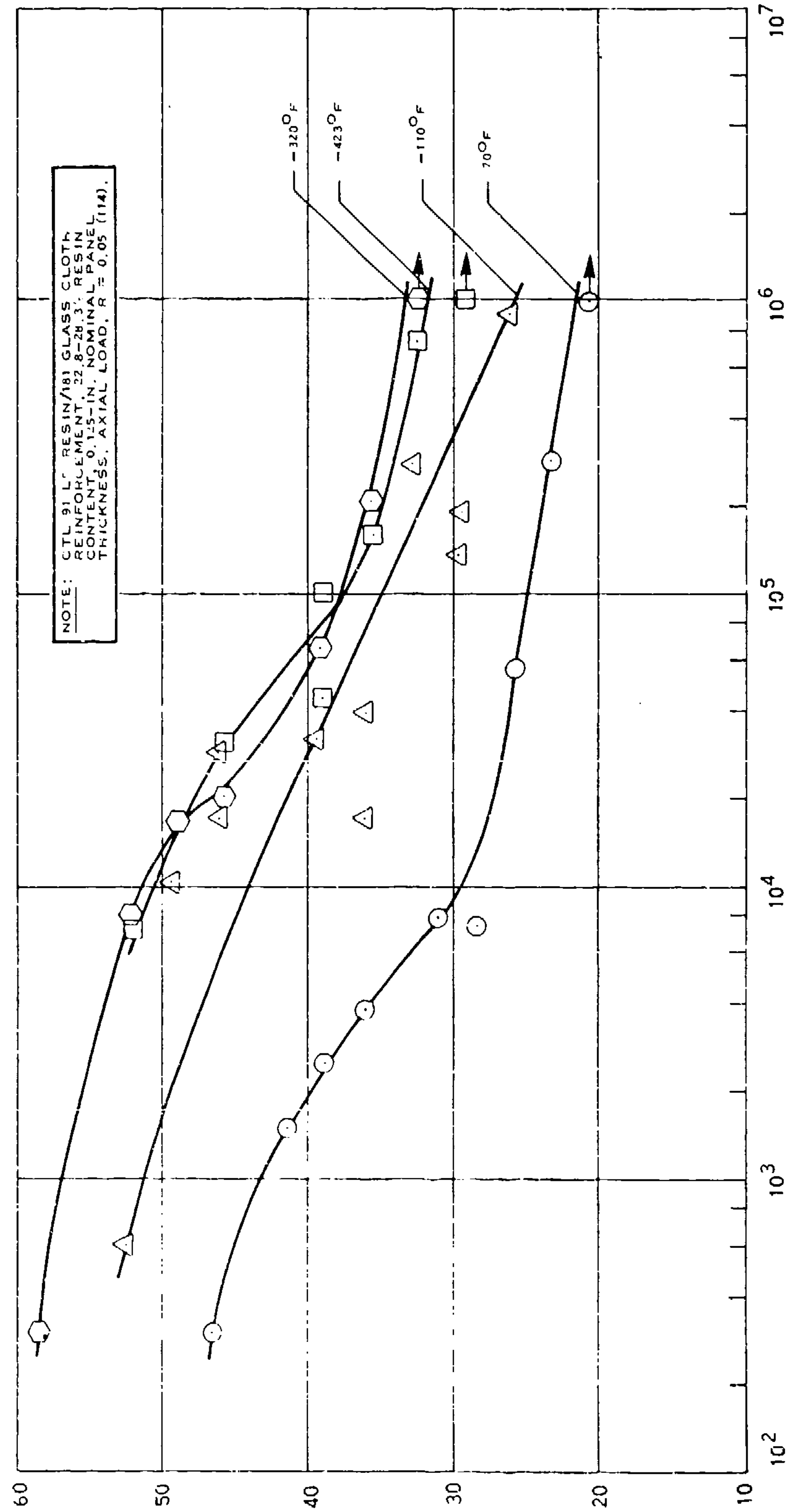


COMPRESSIVE MODULUS OF PHENOLIC-FIBERGLAS LAMINATE

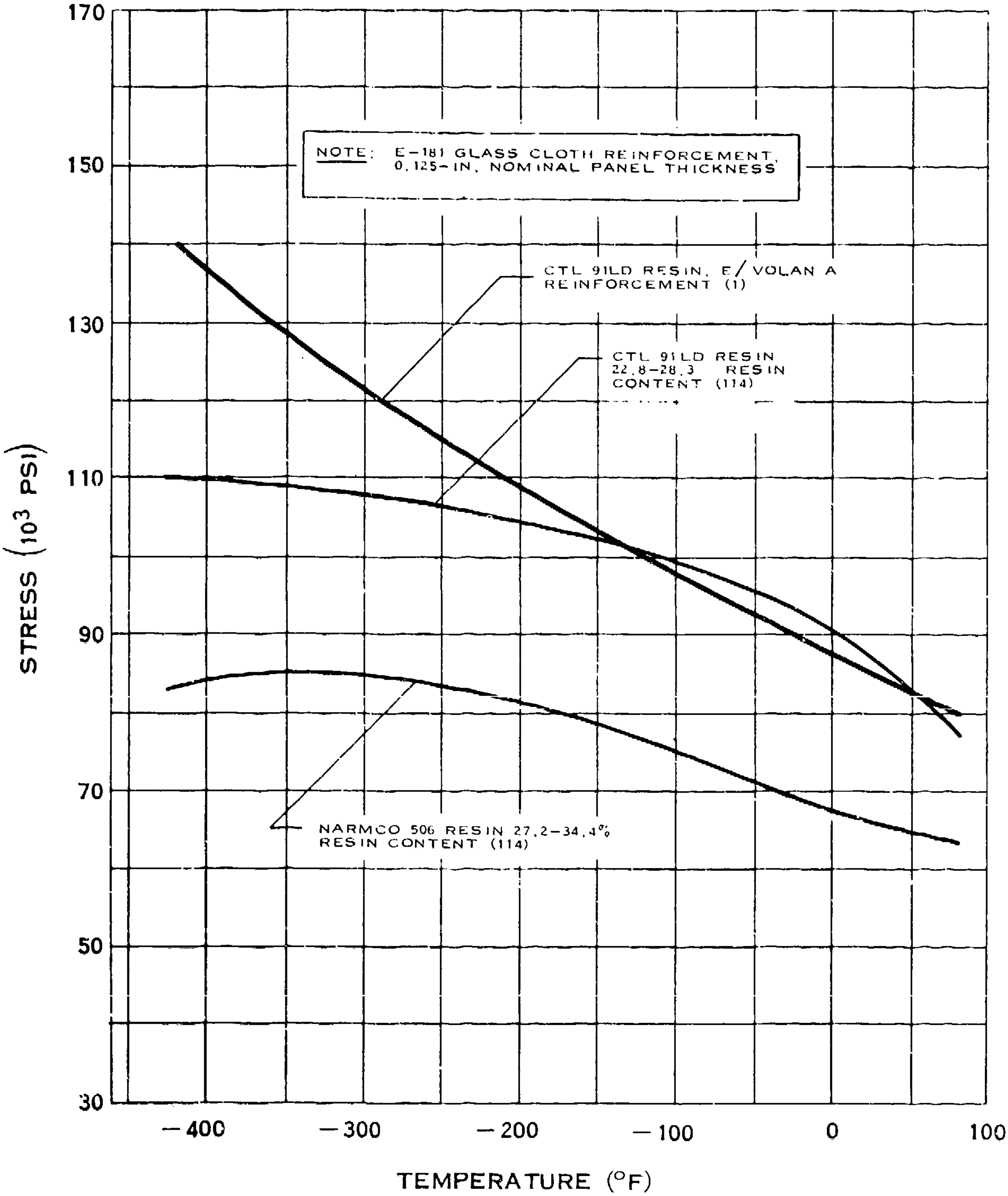
(1-65)



FATIGUE STRENGTH OF PHENOLIC-FIBERGLAS LAMINATE

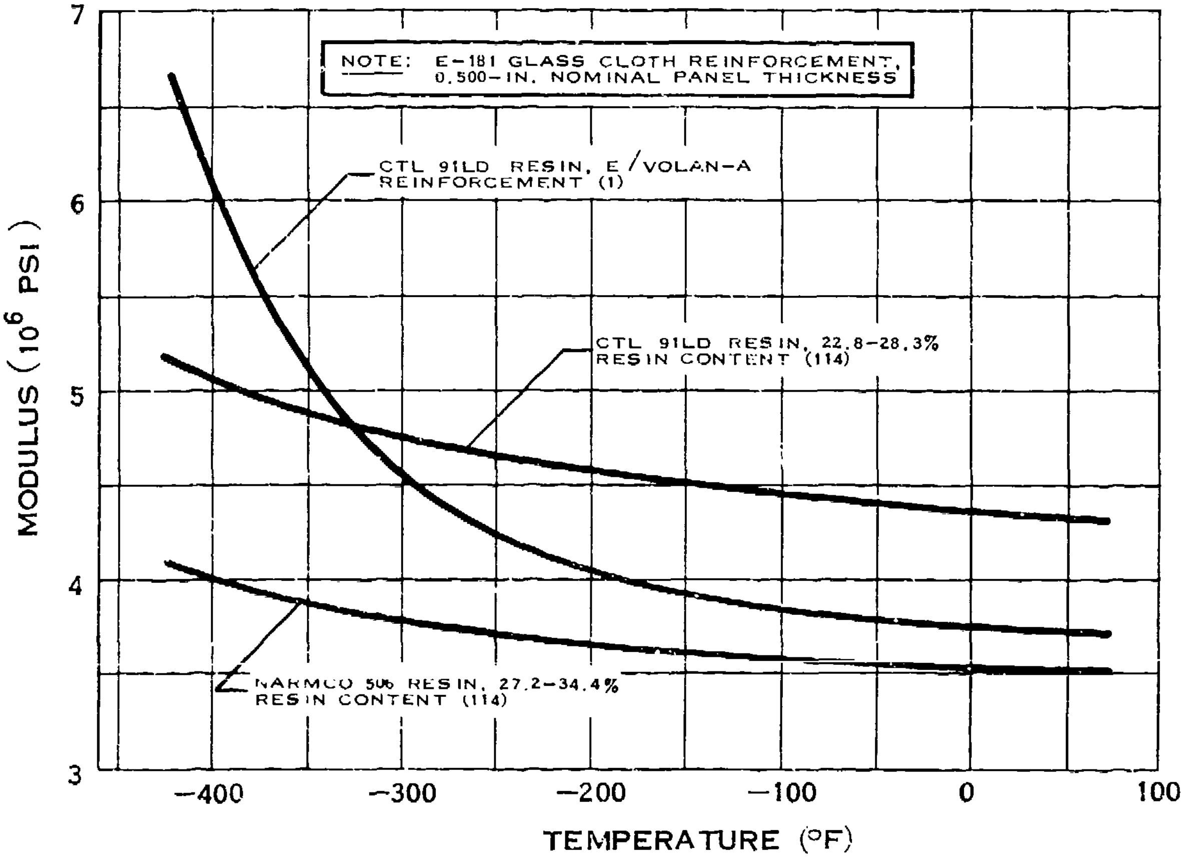


FATIGUE STRENGTH OF PHENOLIC-FIBERGLAS LAMINATE



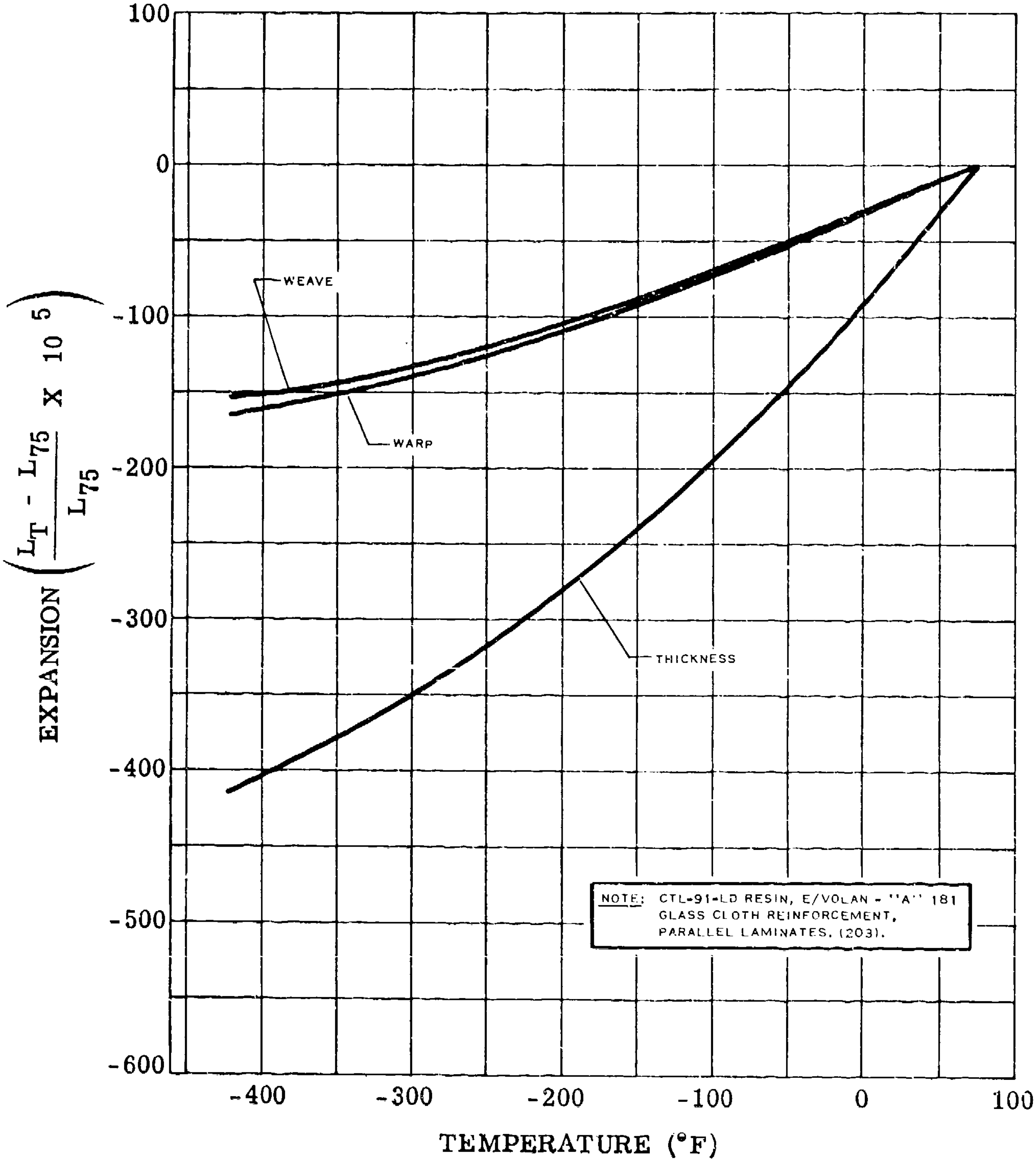
FLEXURAL STRENGTH OF PHENOLIC – FIBERGLAS LAMINATE

(1-65)



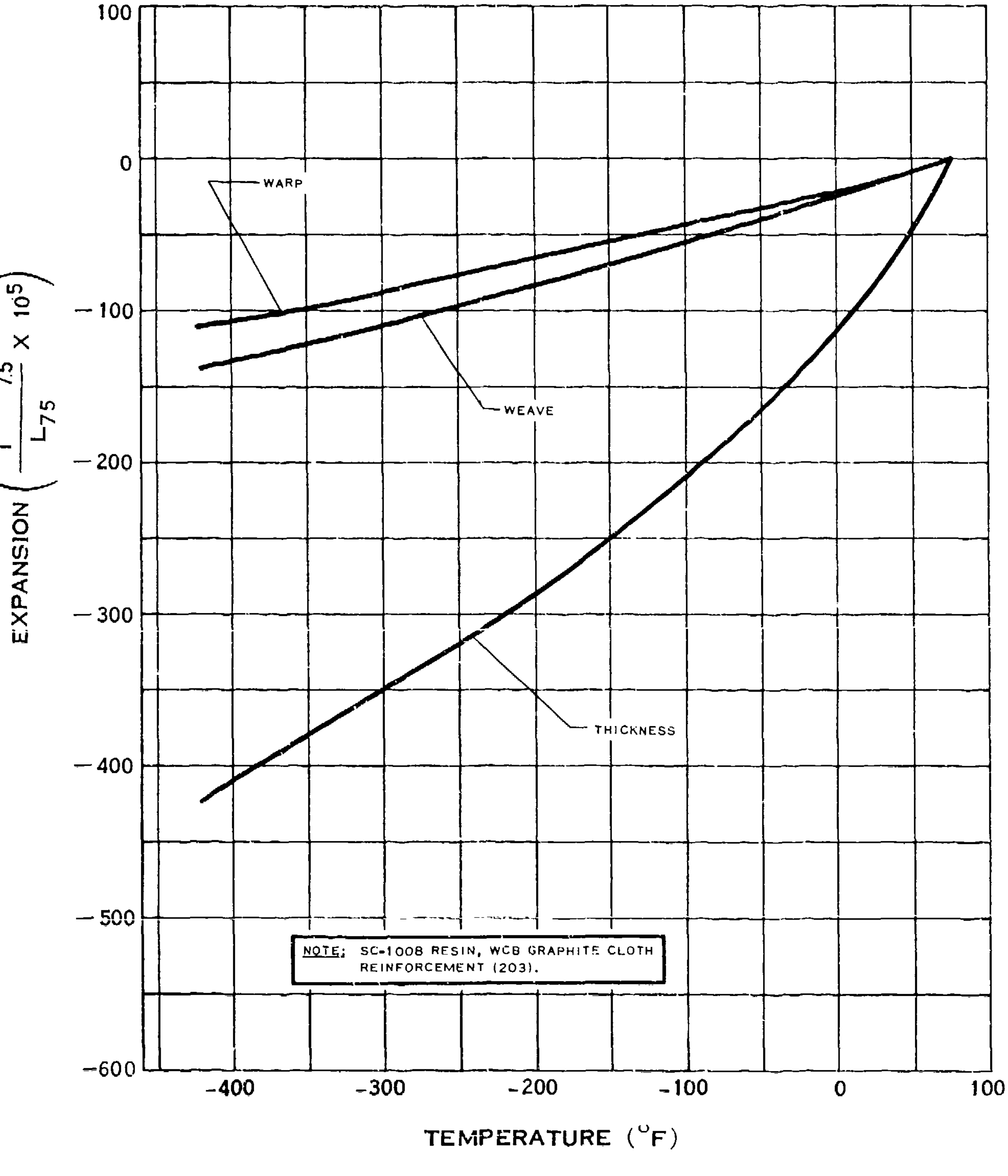
FLEXURAL MODULUS OF PHENOLIC-FIBERGLAS LAMINATE

(1-65)



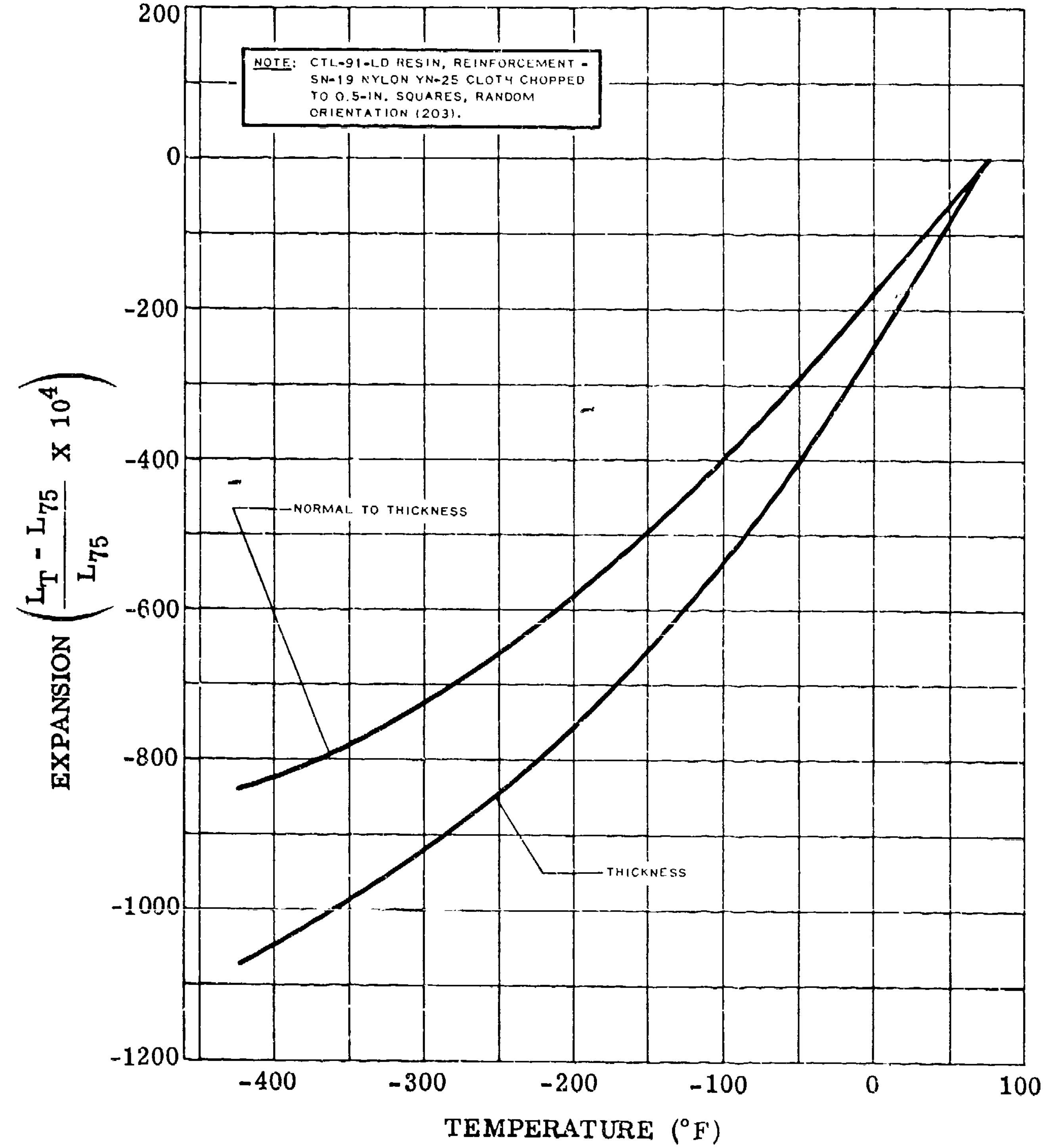
THERMAL EXPANSION OF PHENOLIC-FIBERGLAS LAMINATE

(6-68)



THERMAL EXPANSION OF PHENOLIC-GRAPHITE LAMINATE

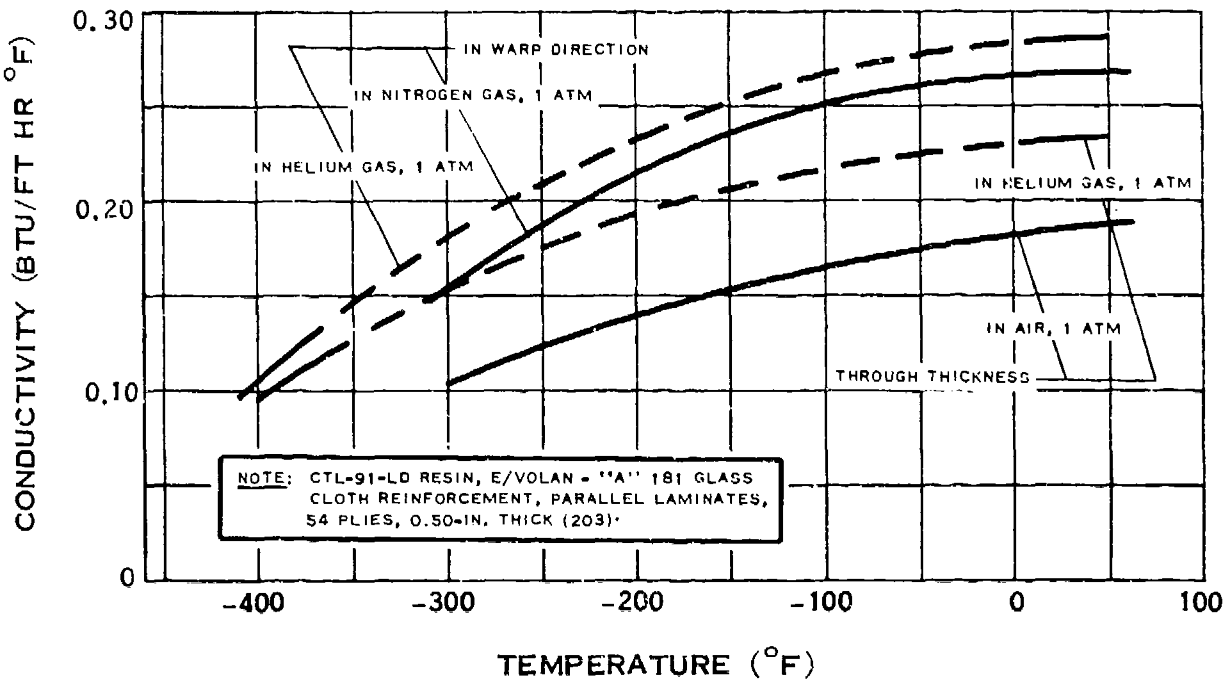
(6-68)



THERMAL EXPANSION OF MOLDED PHENOLIC-NYLON REINFORCED

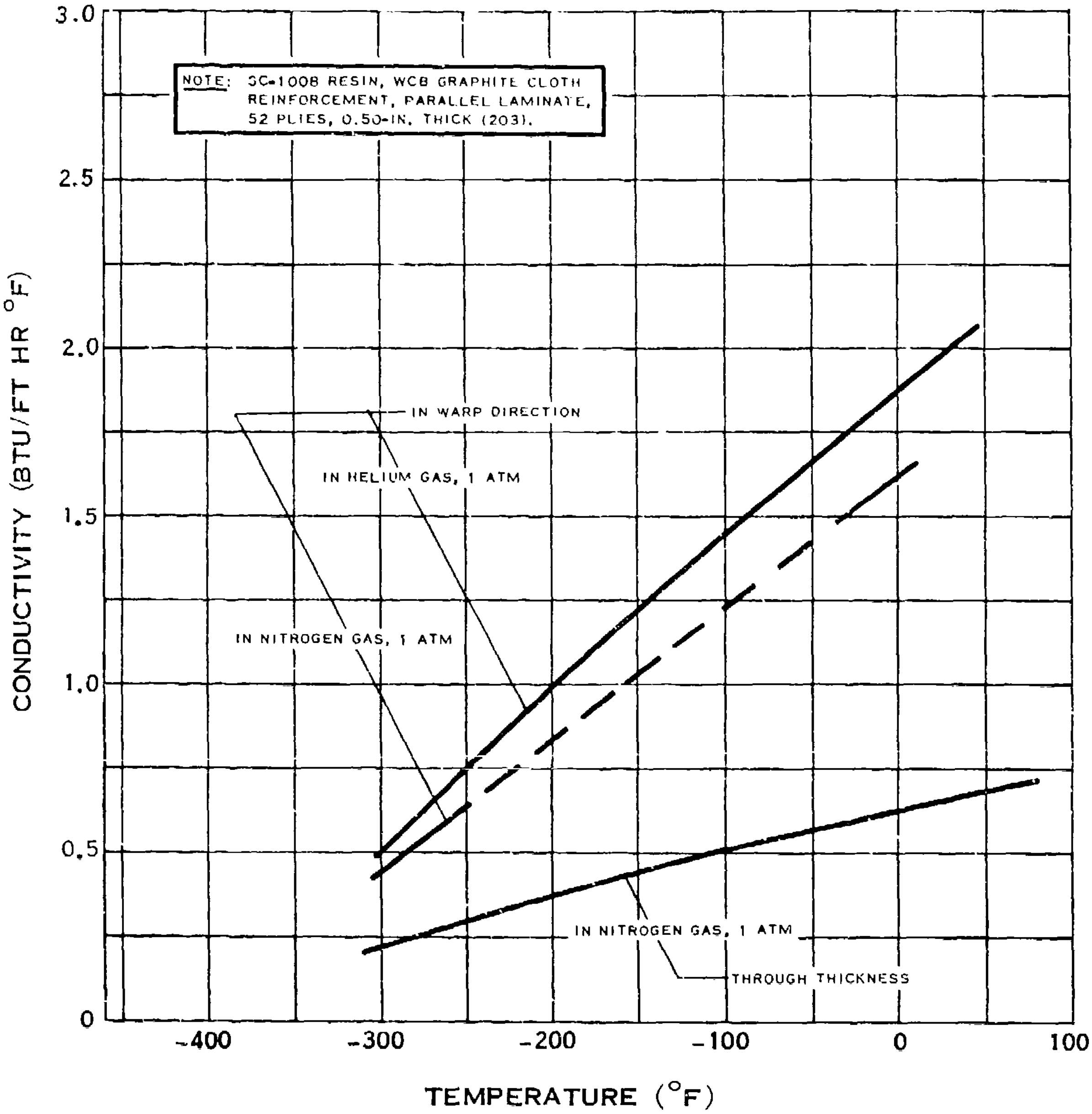
(6-68)

H.2.v



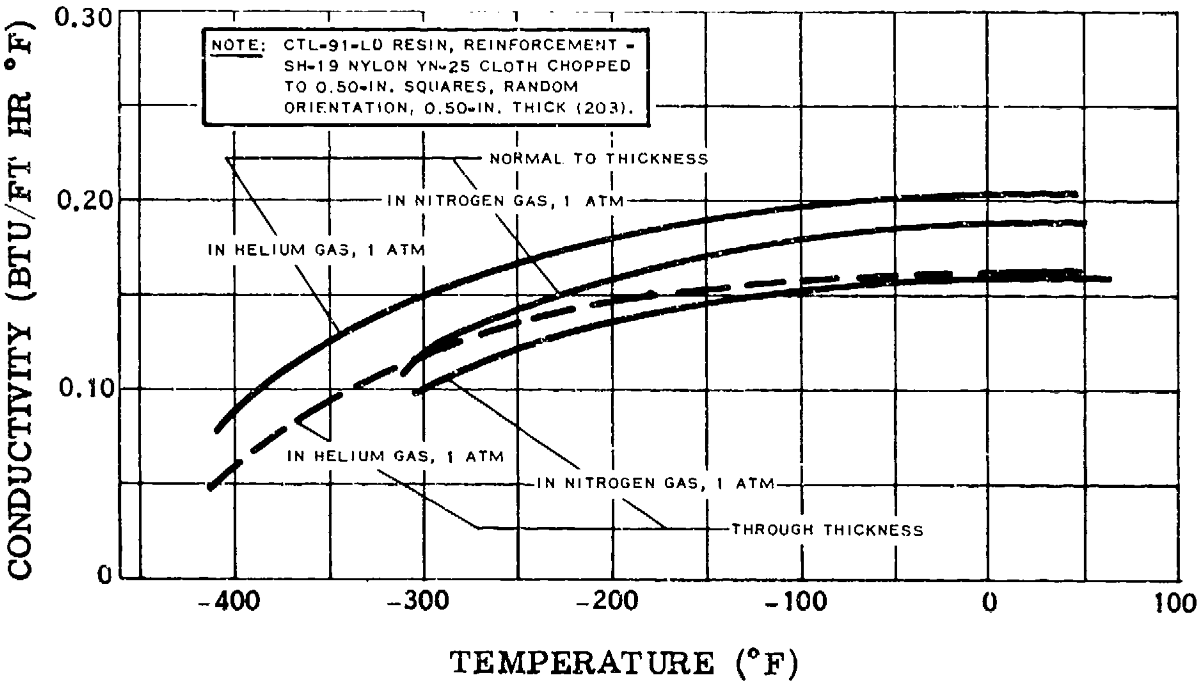
THERMAL CONDUCTIVITY OF PHENOLIC-FIBERGLAS LAMINATE

(6-68)



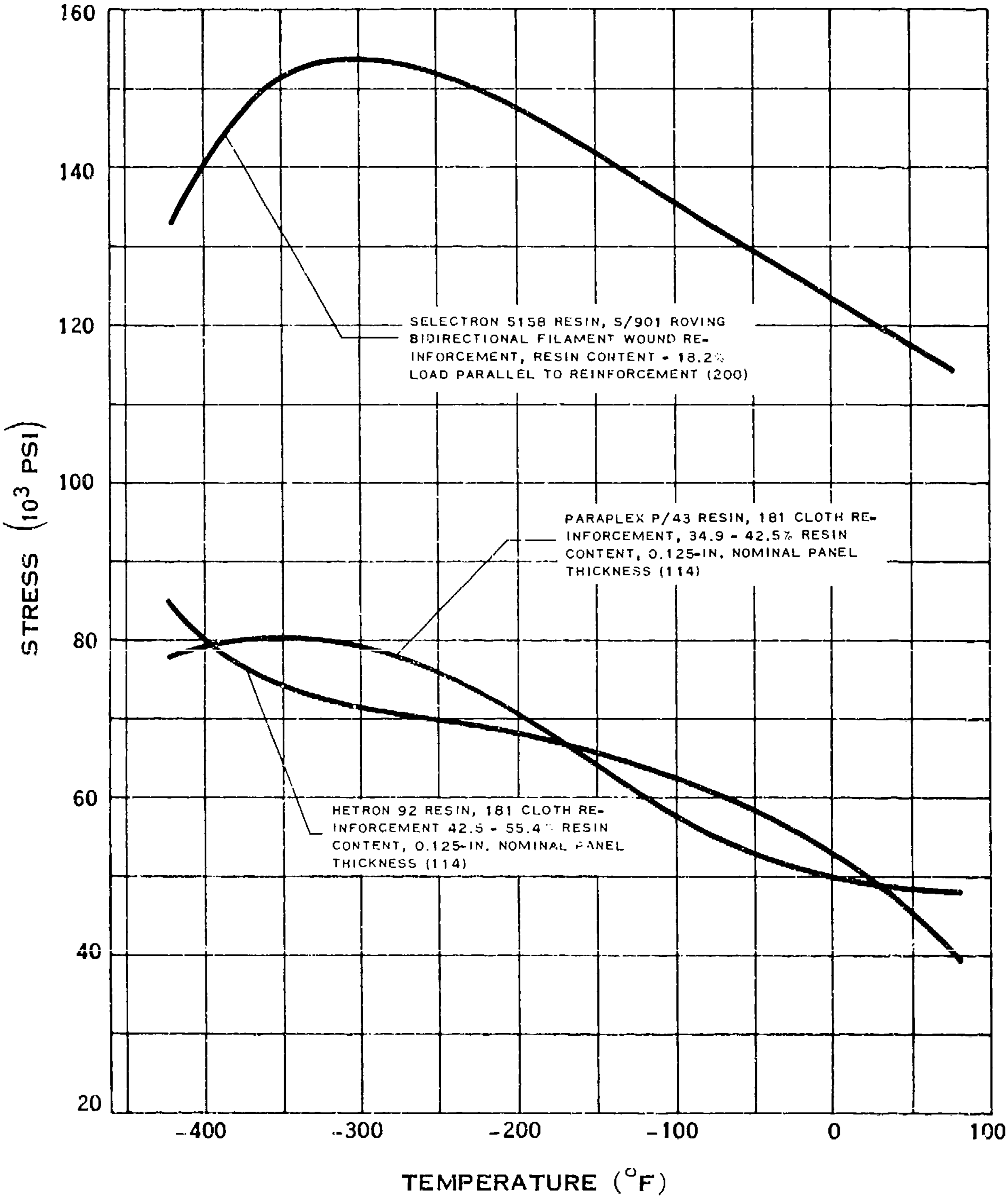
THERMAL CONDUCTIVITY OF PHENOLIC-GRAPHITE LAMINATE

(6-68)



THERMAL CONDUCTIVITY OF MOLDED PHENOLIC-NYLON REINFORCED

(6-68)



TENSILE STRENGTH OF POLYESTER – FIBERGLAS LAMINATE

(6-68)

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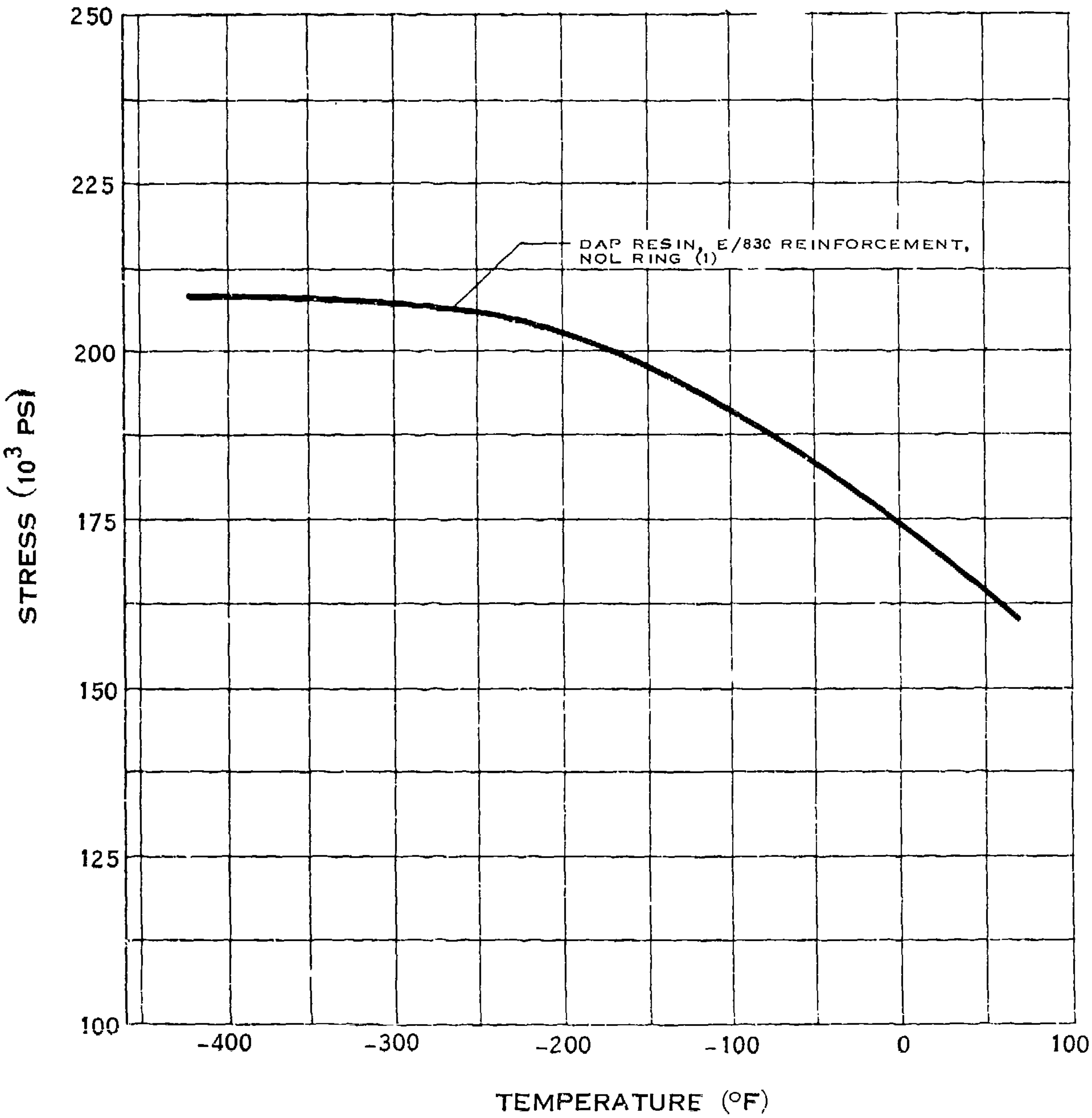
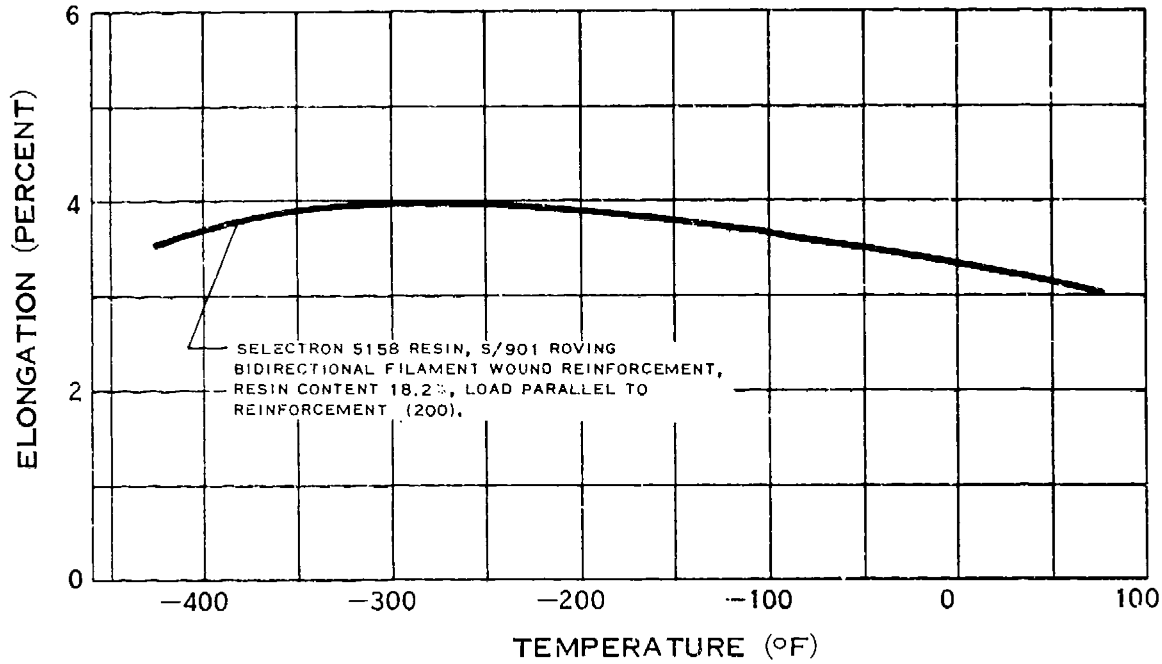
H.3.b-1

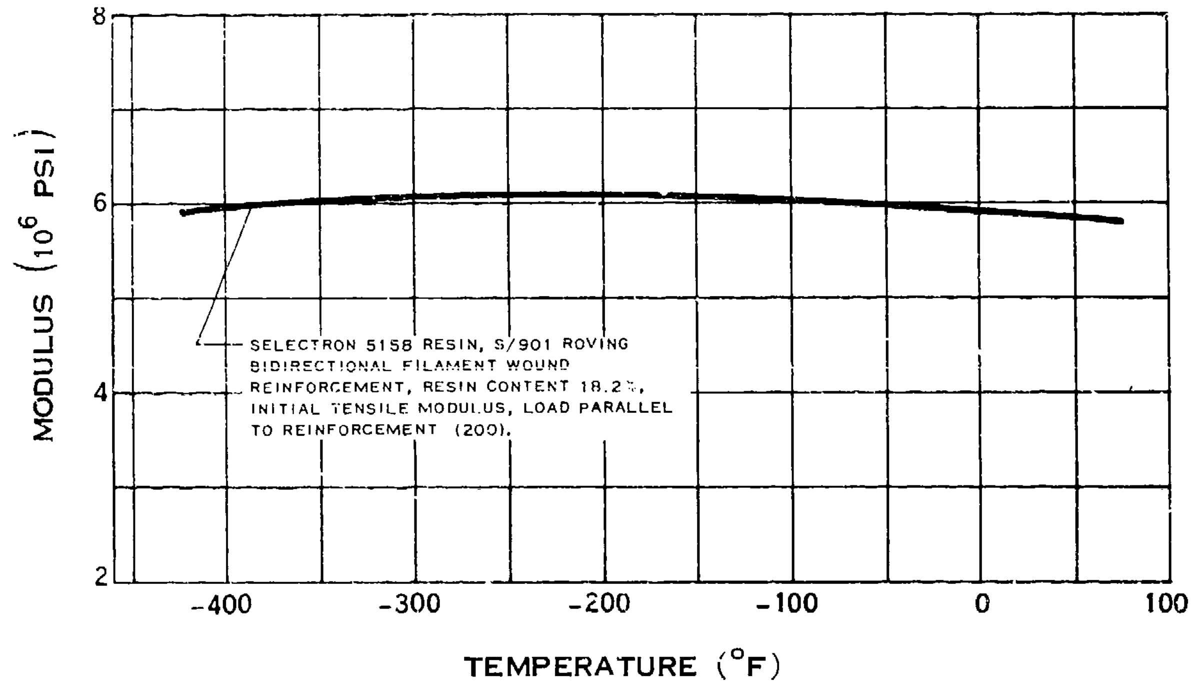


TENSILE STRENGTH OF POLYESTER-FIBERGLAS FILAMENT WOUND RINGS

(1-65)



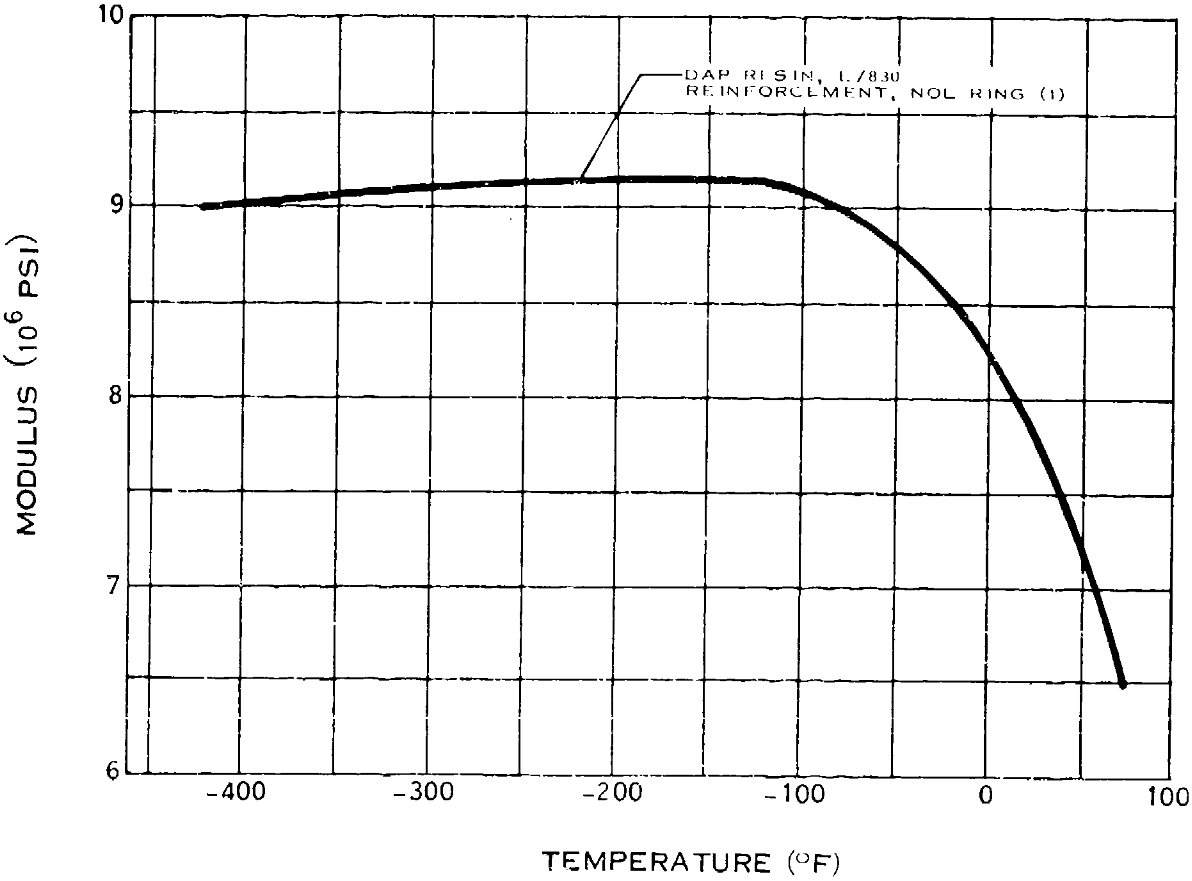
ELONGATION OF POLYESTER FIBERGLAS LAMINATE



MODULUS OF ELASTICITY OF POLYESTER FIBERGLAS LAMINATE

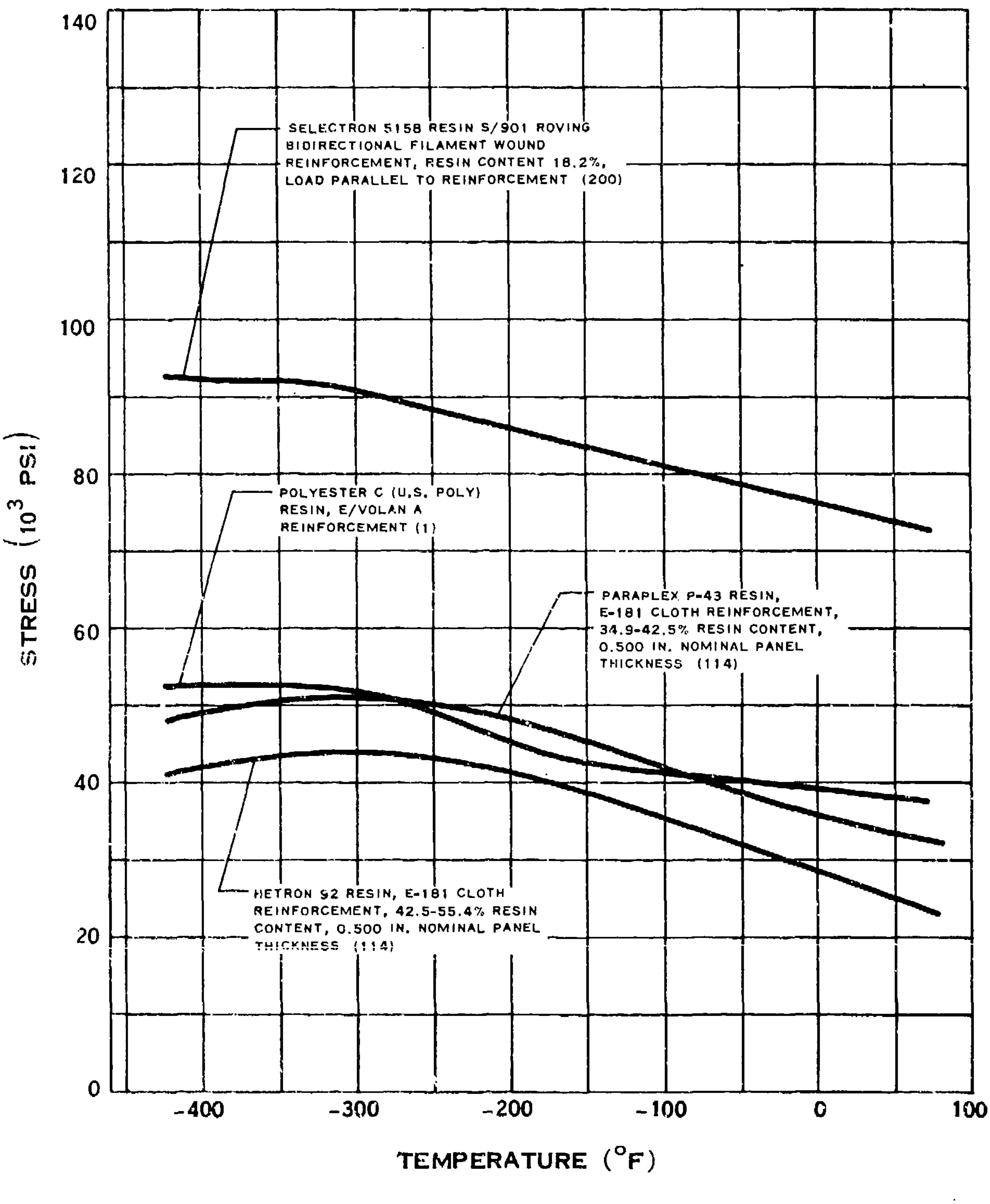
(6-68)

H.3.i-1



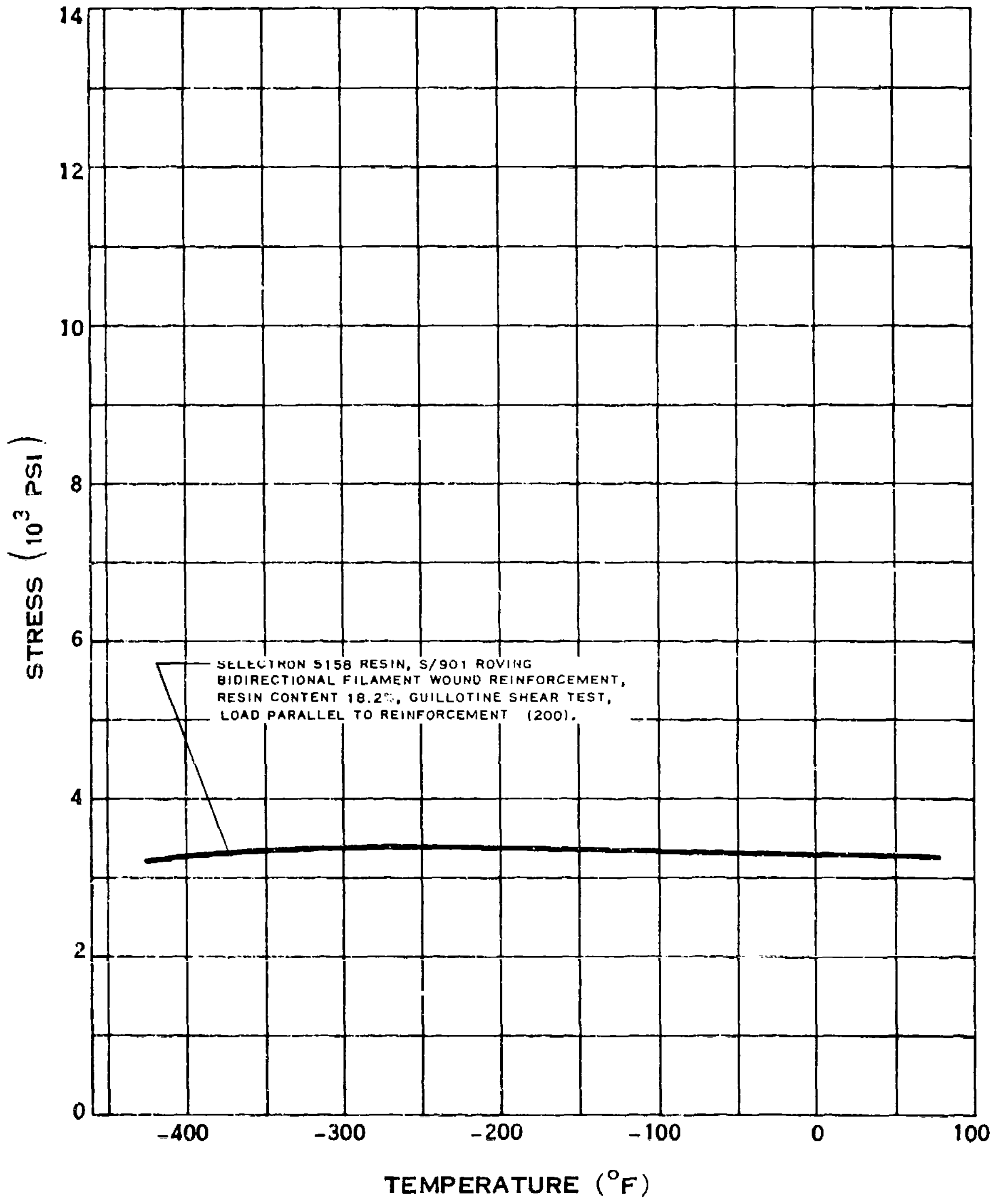
MODULUS OF ELASTICITY OF POLYESTER-FIBERGLAS FILAMENT-WOUND RINGS

(6-68)



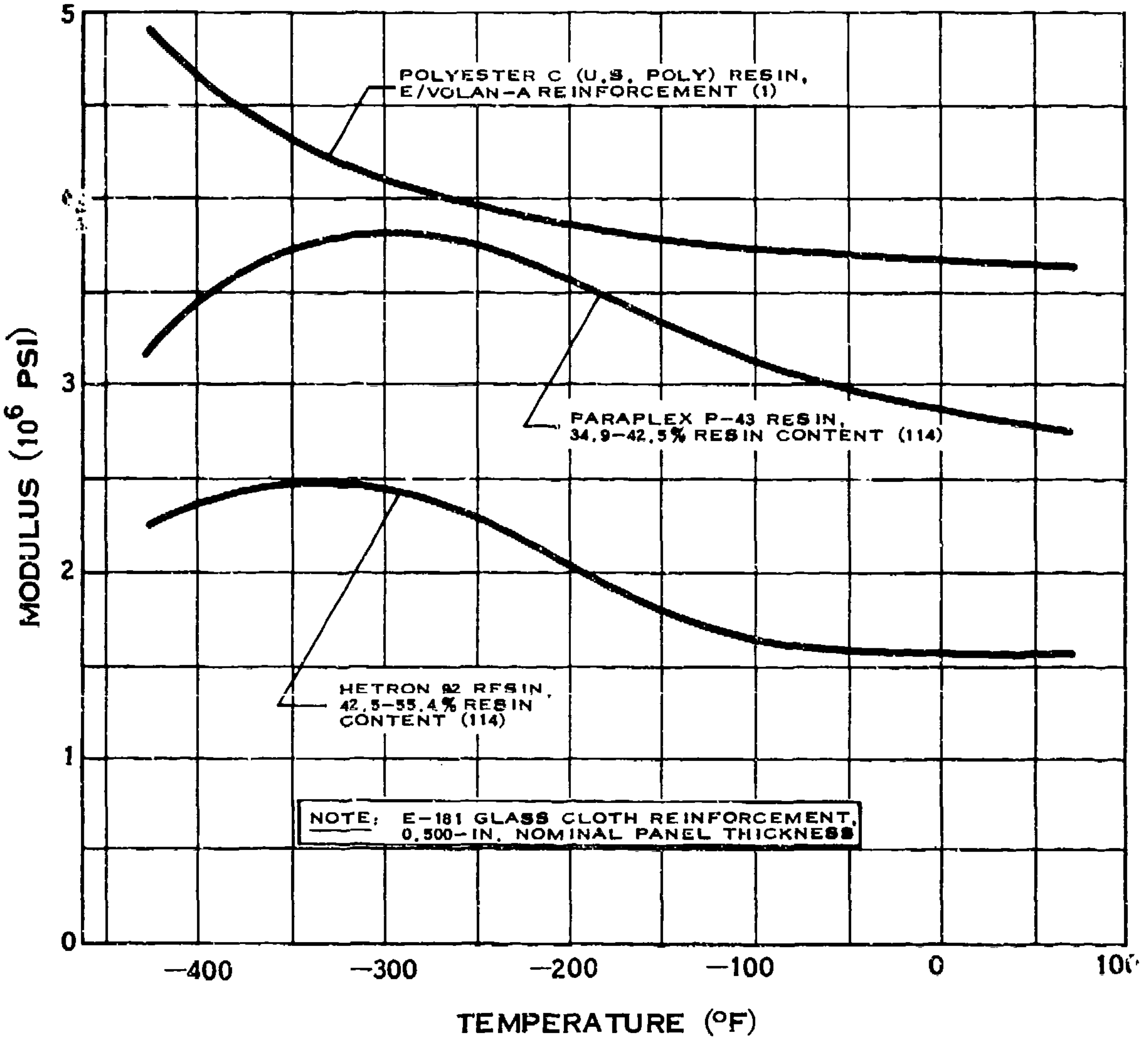
COMPRESSIVE STRENGTH OF POLYESTER-FIBERGLAS LAMINATE

(6-68)

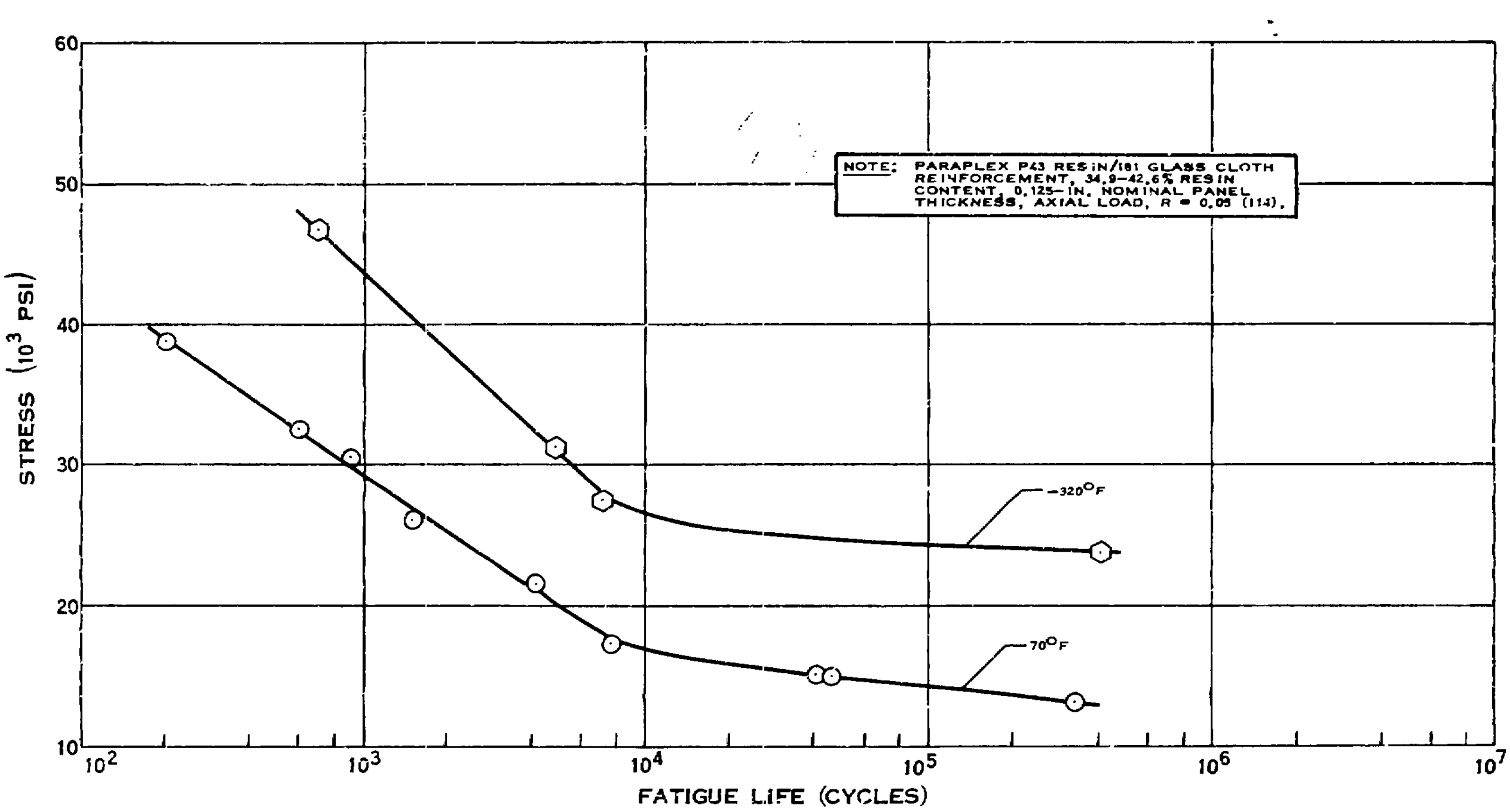


SHEAR STRENGTH OF POLYESTER-FIBERGLAS LAMINATE

(6-68)

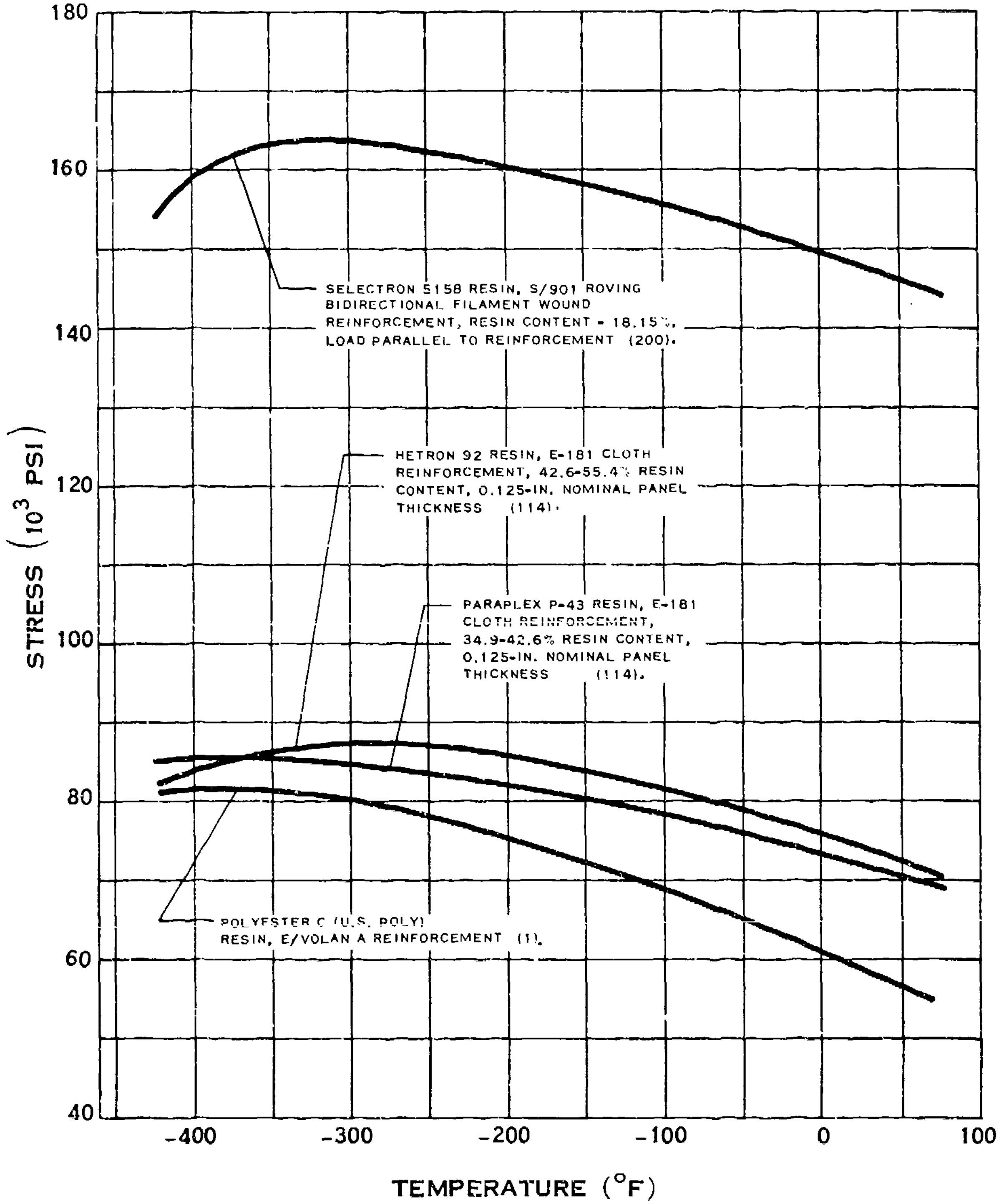


COMPRESSIVE MODULUS OF POLYESTER-FIBERGLAS LAMINATE



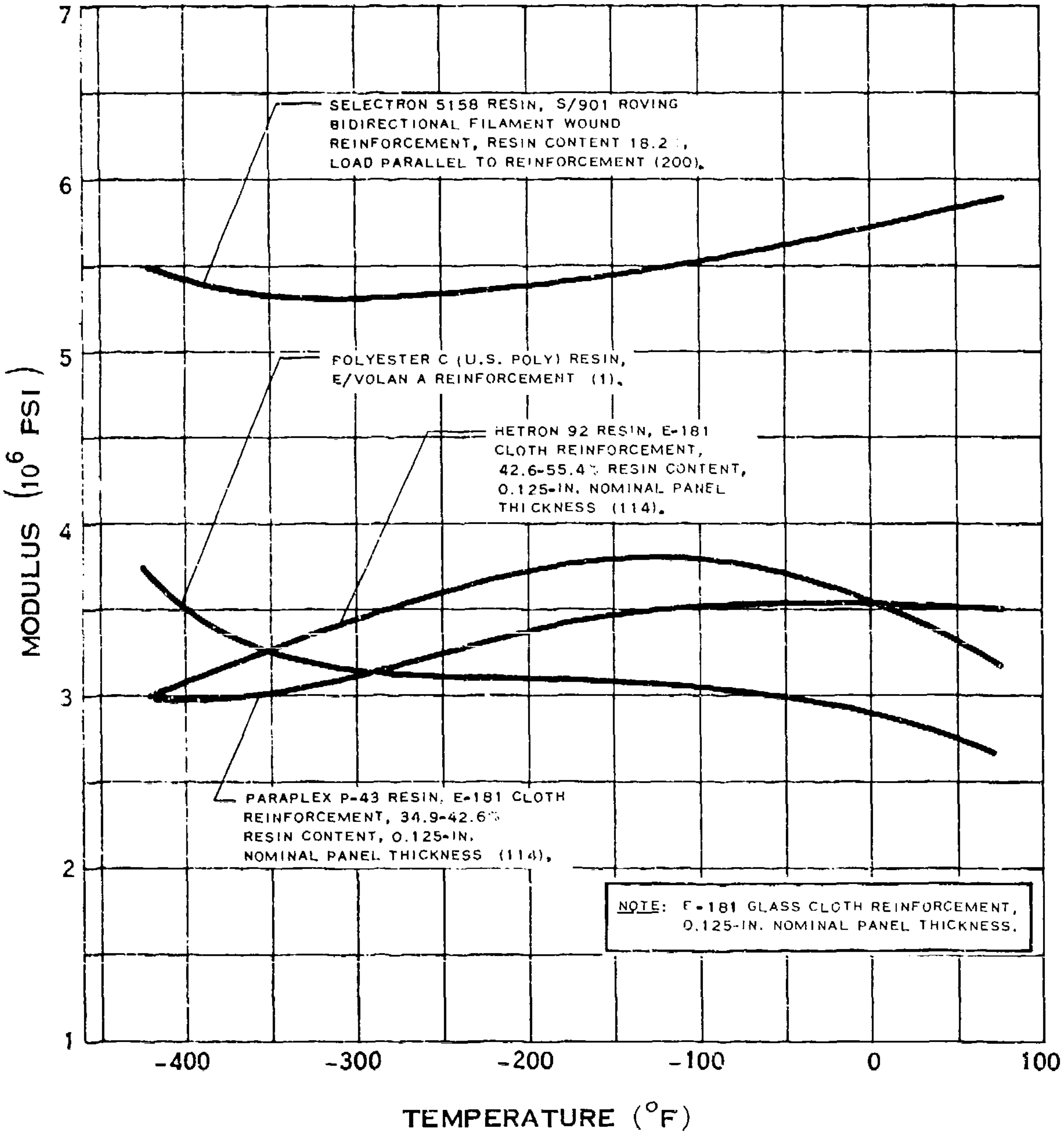
FATIGUE STRENGTH OF POLYESTER-FIBERGLAS LAMINATE

(7–64)



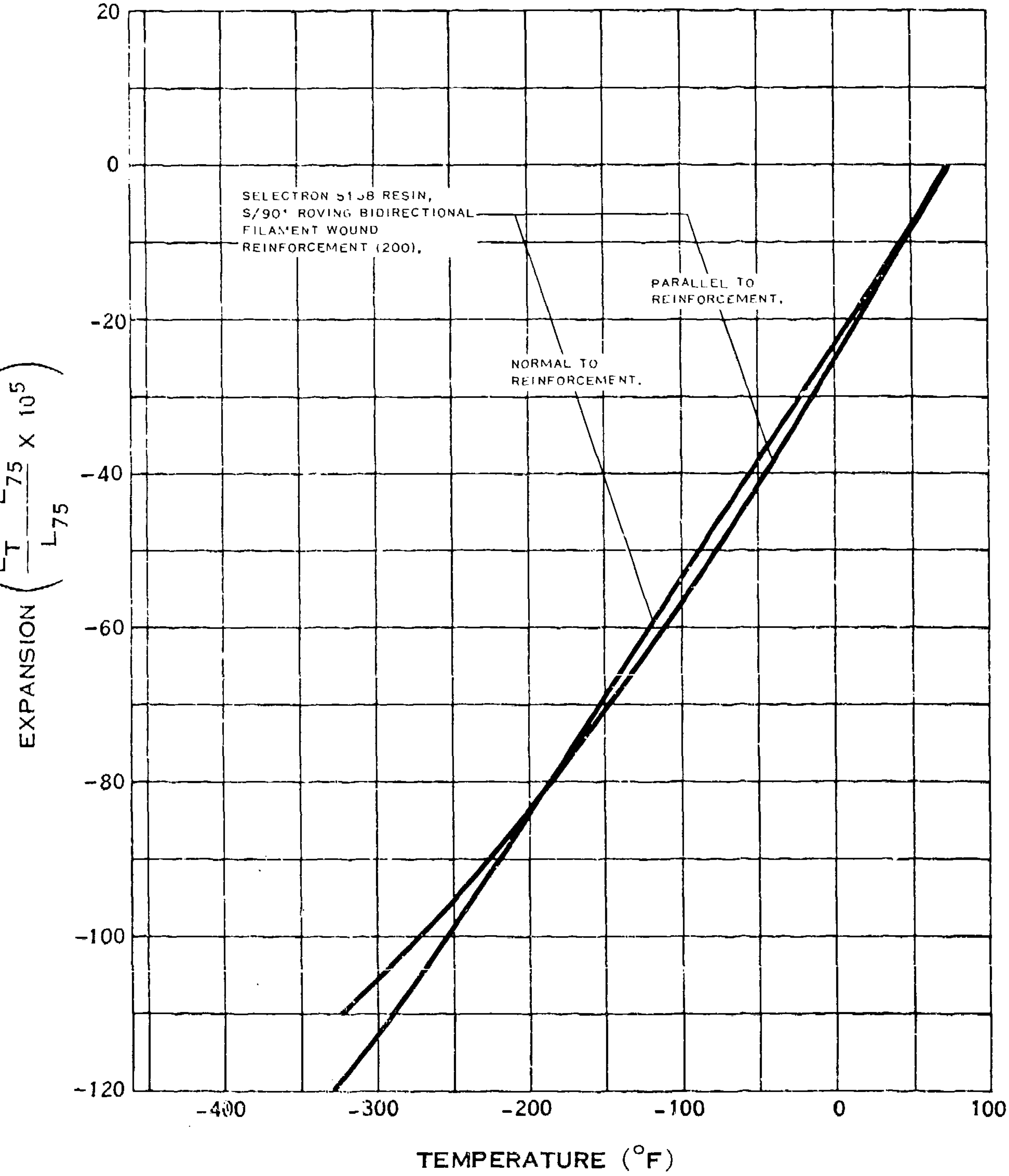
FLEXURAL STRENGTH OF POLYESTER-FIBERGLAS LAMINATE

(6-68)



FLEXURAL MODULUS OF POLYESTER-FIBERGLAS LAMINATE

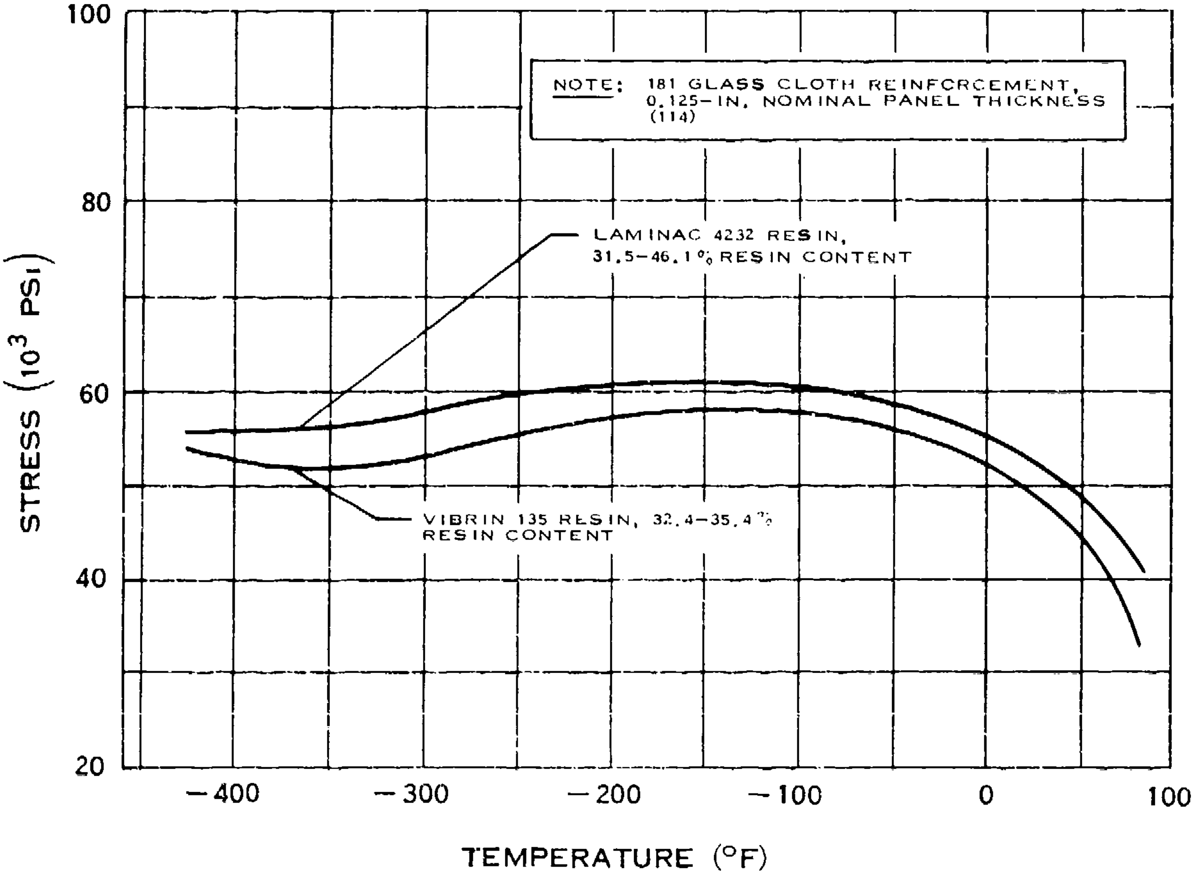
(6-68)



THERMAL EXPANSION OF POLYESTER FIBERGLAS LAMINATE

(6-68)

H.4.b



TENSILE STRENGTH OF HIGH TEMPERATURE POLYESTER - FIBERGLAS LAMINATE

(7-64)

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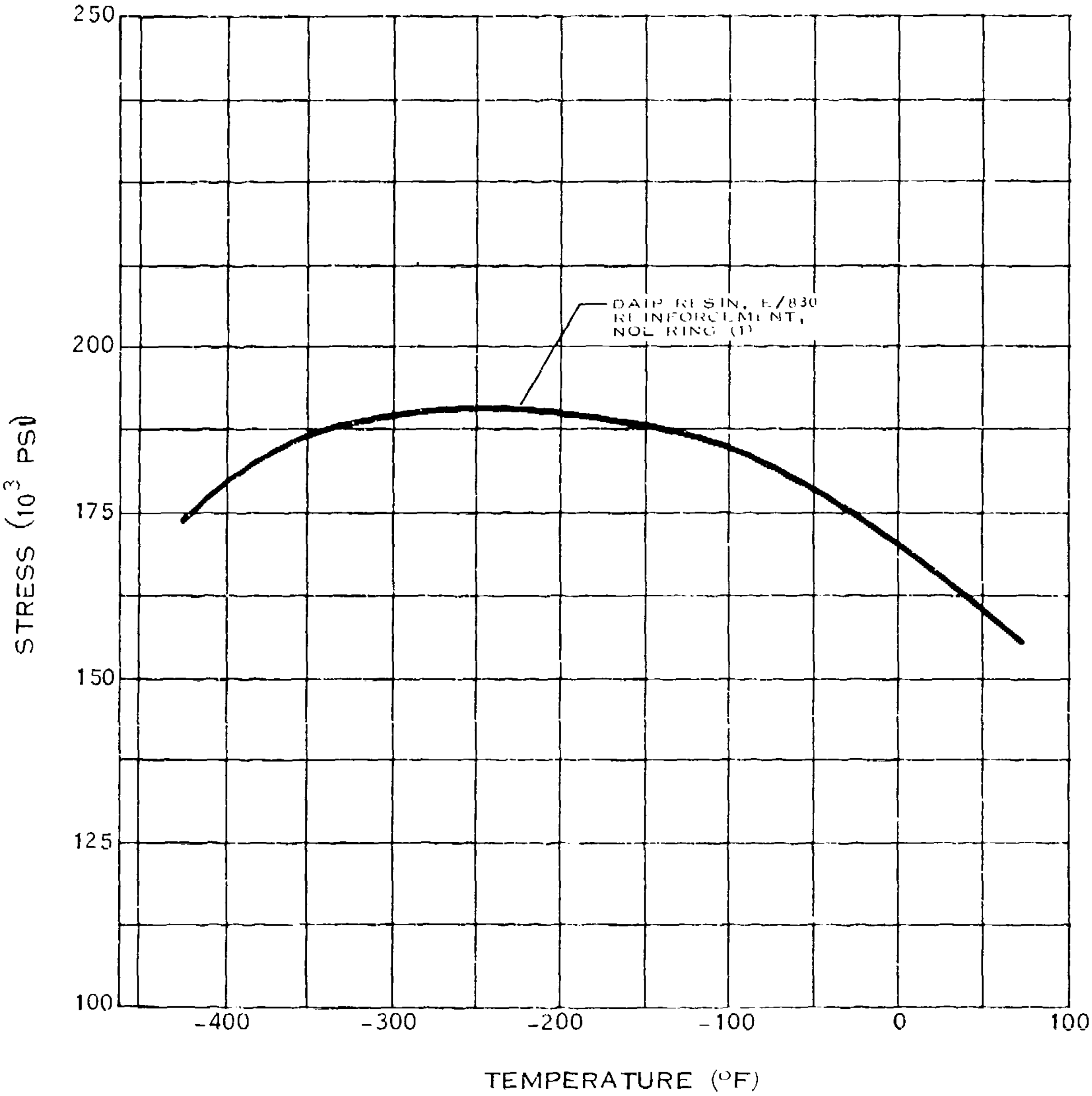
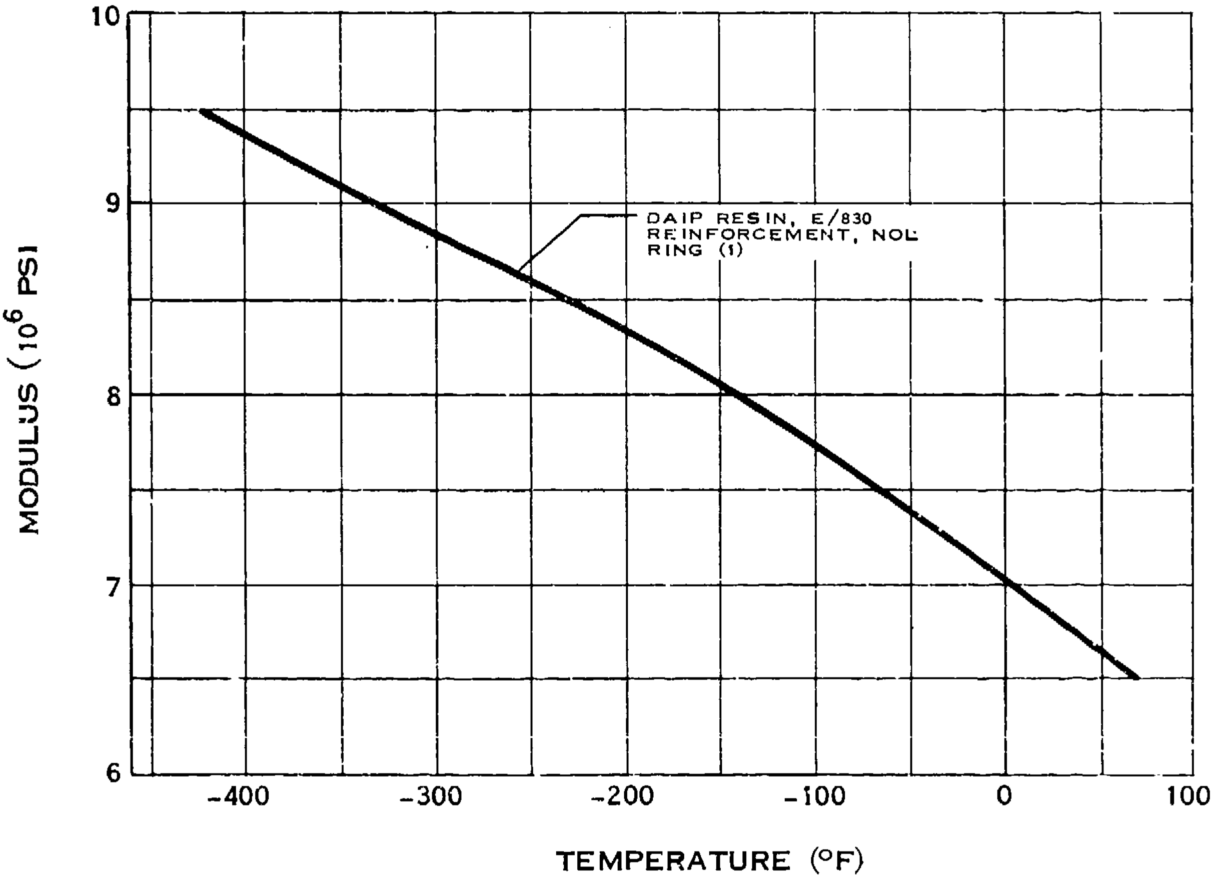
H.4.b-1



TENSILE STRENGTH OF HIGH TEMPERATURE POLYESTER-FIBERGLAS FILAMENT WOUND RINGS

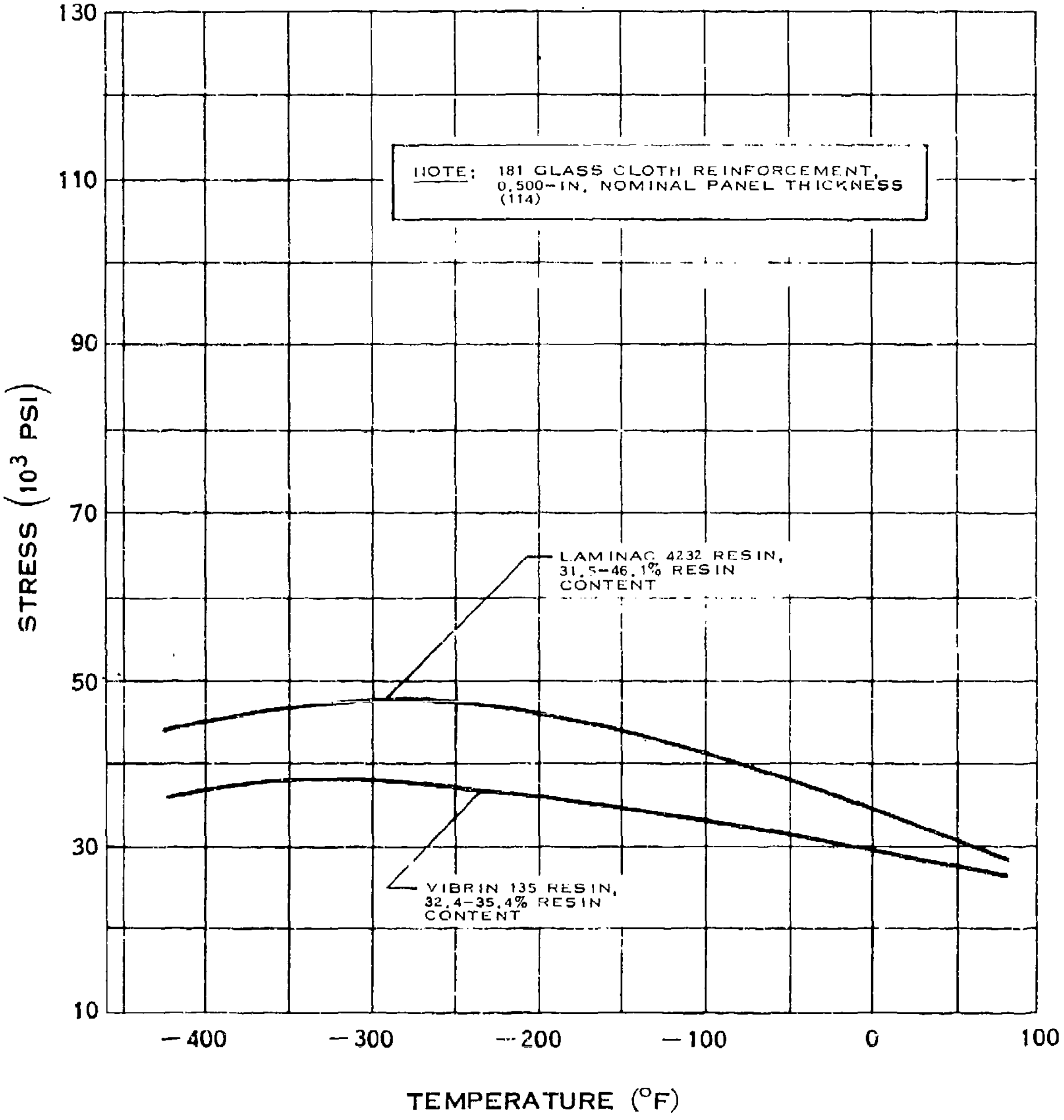
(1-65)

H.4.i



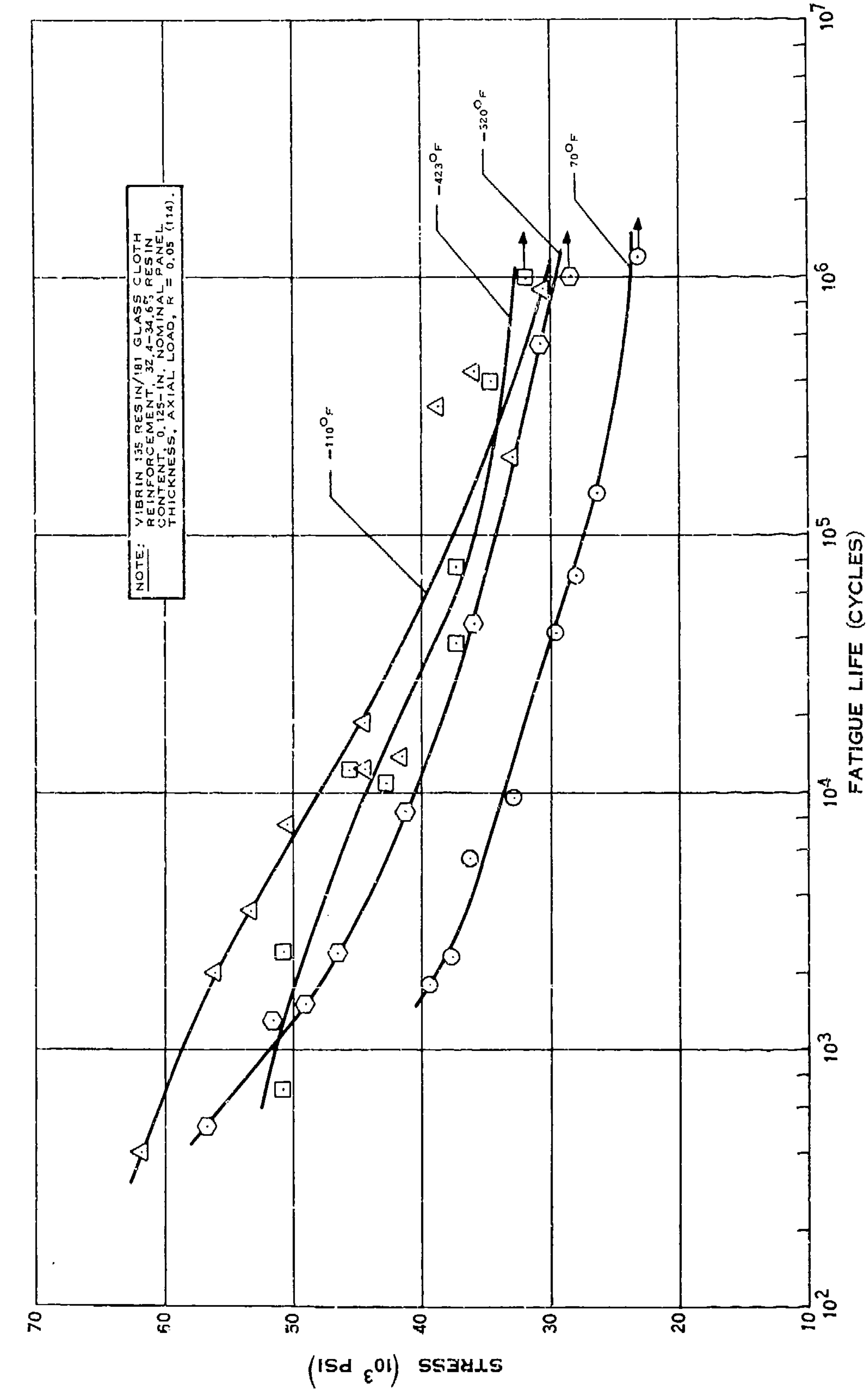
MODULUS OF ELASTICITY OF HIGH TEMPERATURE POLYESTER-FIBERGLAS FILAMENT WOUND RINGS

(1-65)

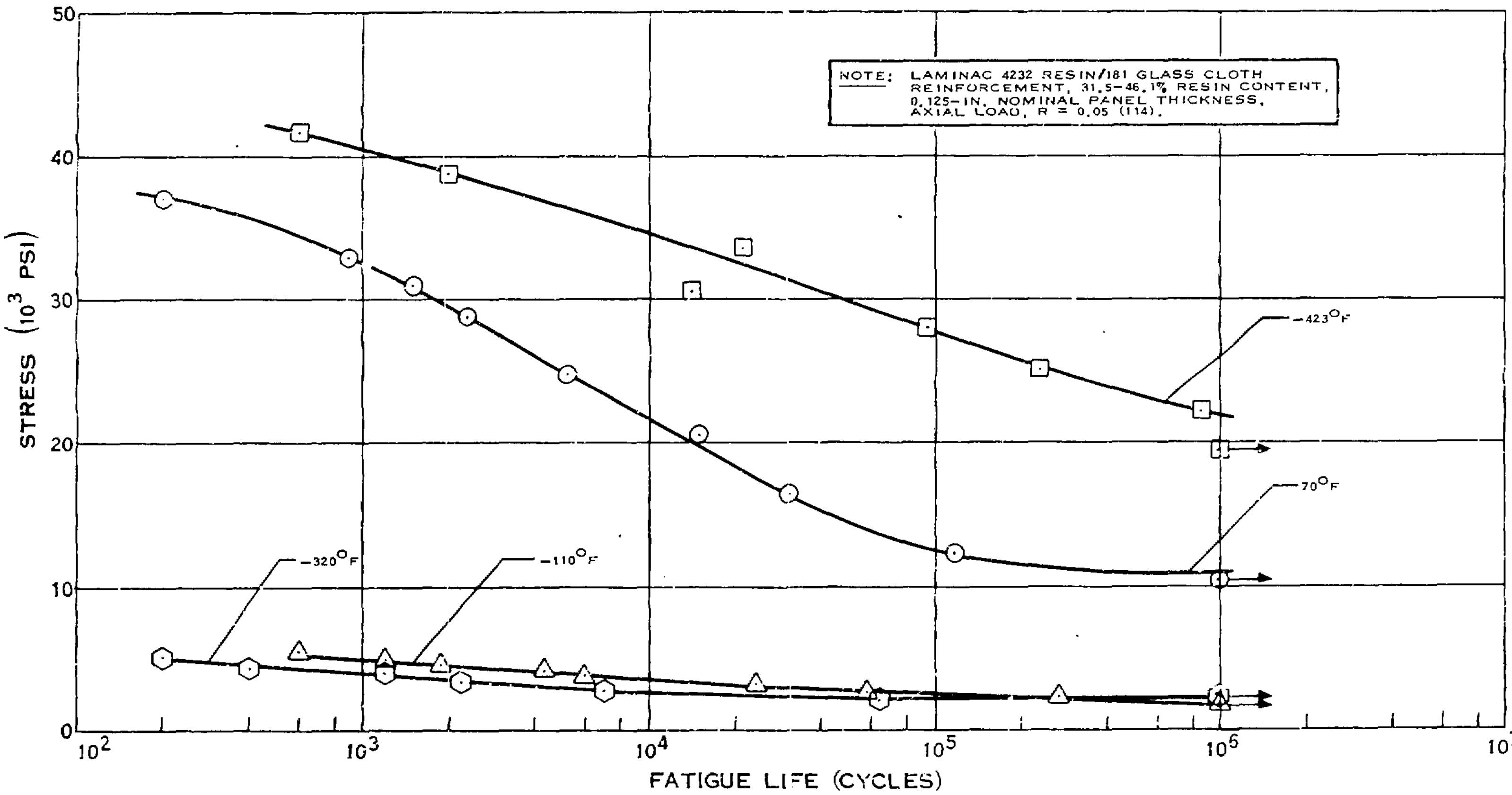


COMPRESSIVE STRENGTH OF HIGH TEMPERATURE POLYESTER – FIBERGLAS LAMINATE

(7–64)

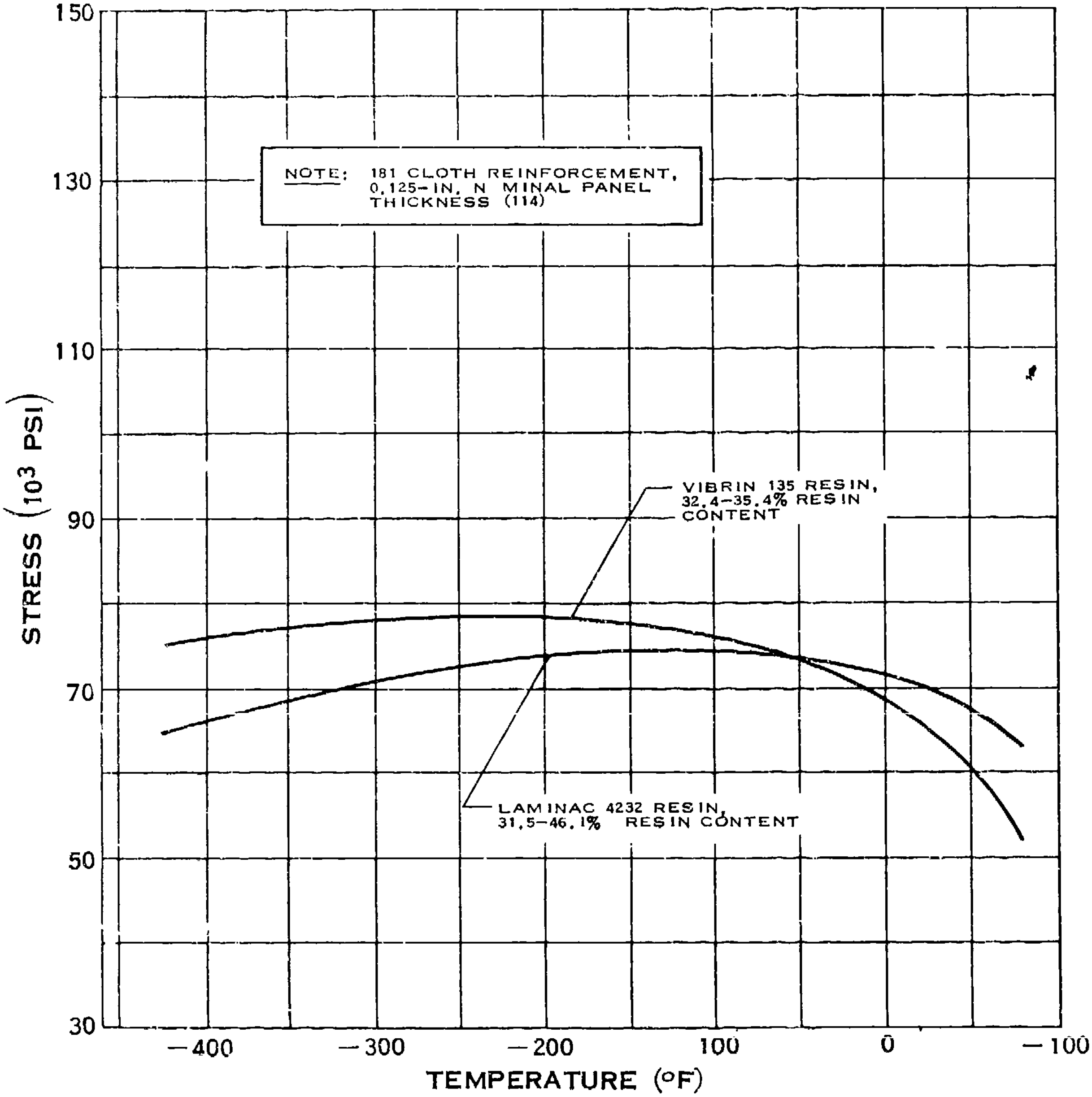


FATIGUE STRENGTH OF HIGH TEMPERATURE POLYESTER-FIBERGLAS LAMINATE



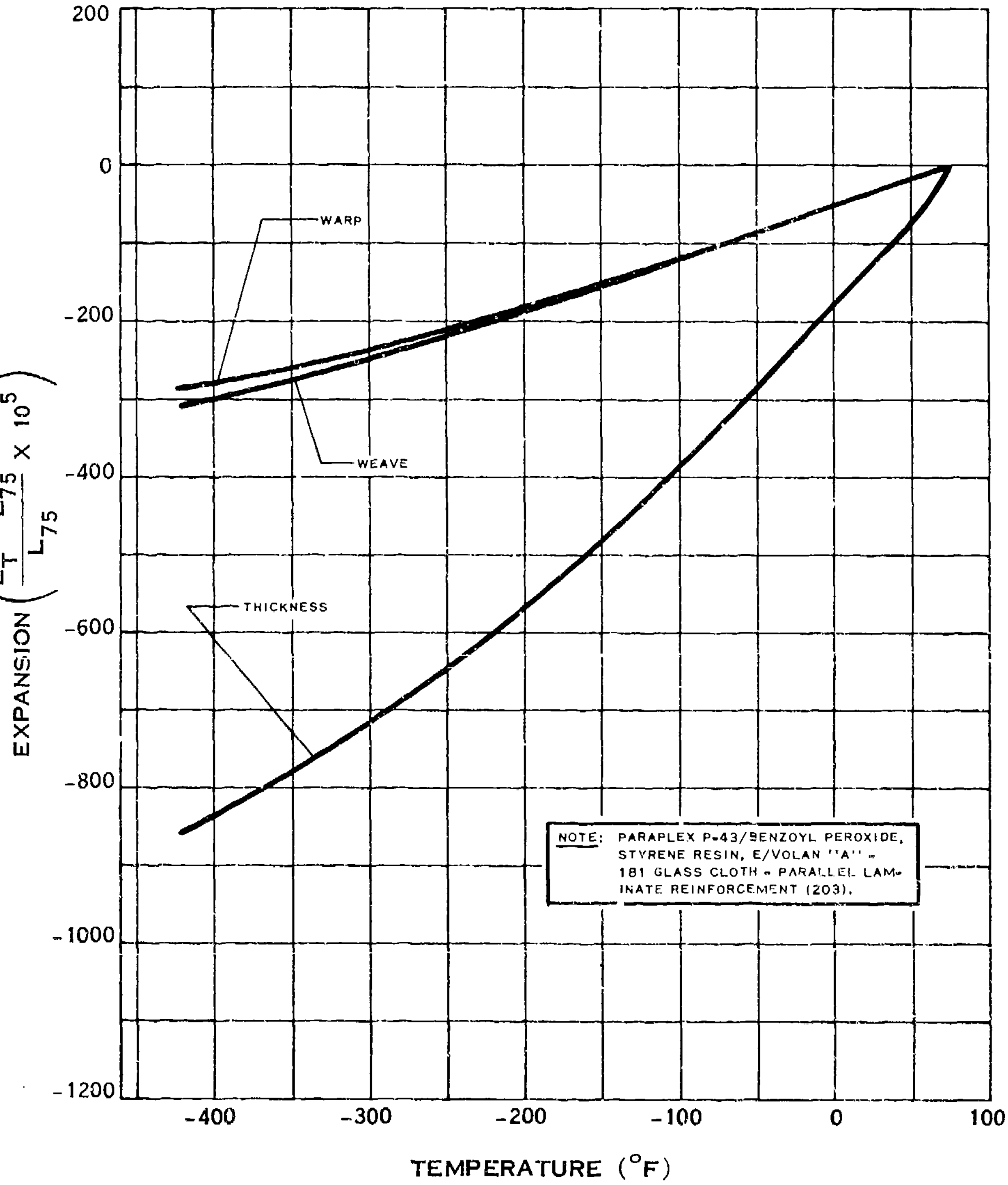
FATIGUE STRENGTH OF HIGH TEMPERATURE POLYESTER-FIBERGLAS LAMINATE

(7-64)



FLEXURAL STRENGTH OF HIGH TEMPERATURE POLYESTER – FIBERGLASS LAMINATE

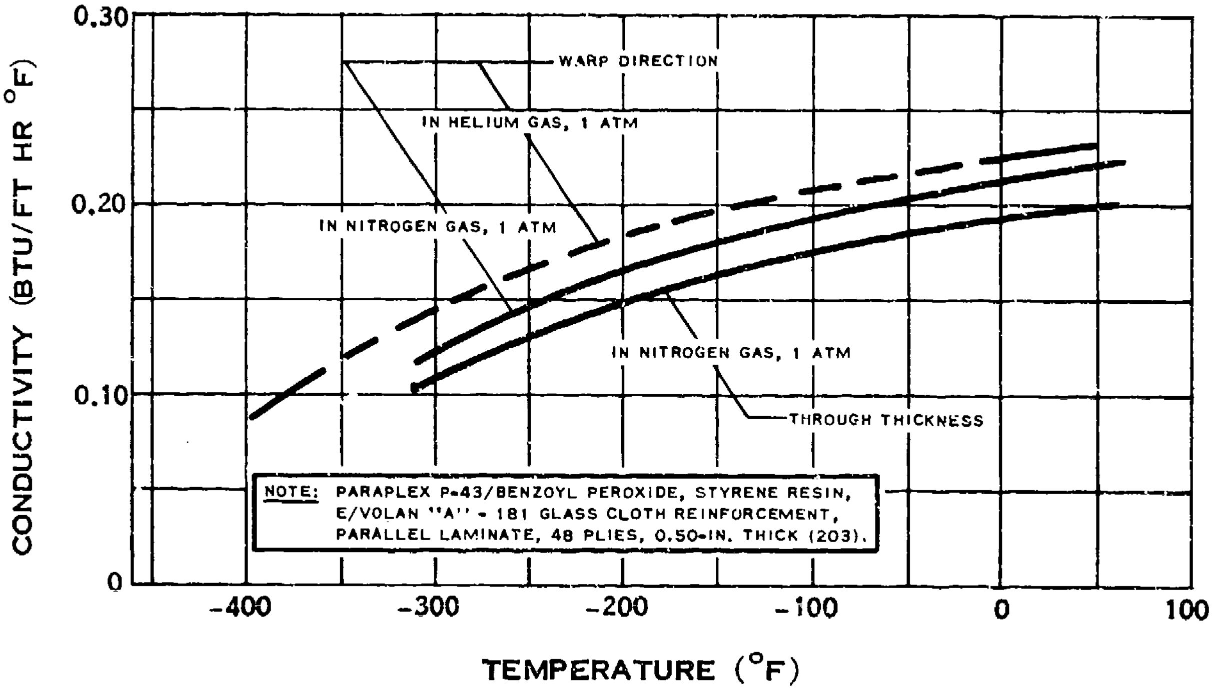
(7-64)



THERMAL EXPANSION OF POLYESTER-FIBERGLAS LAMINATE

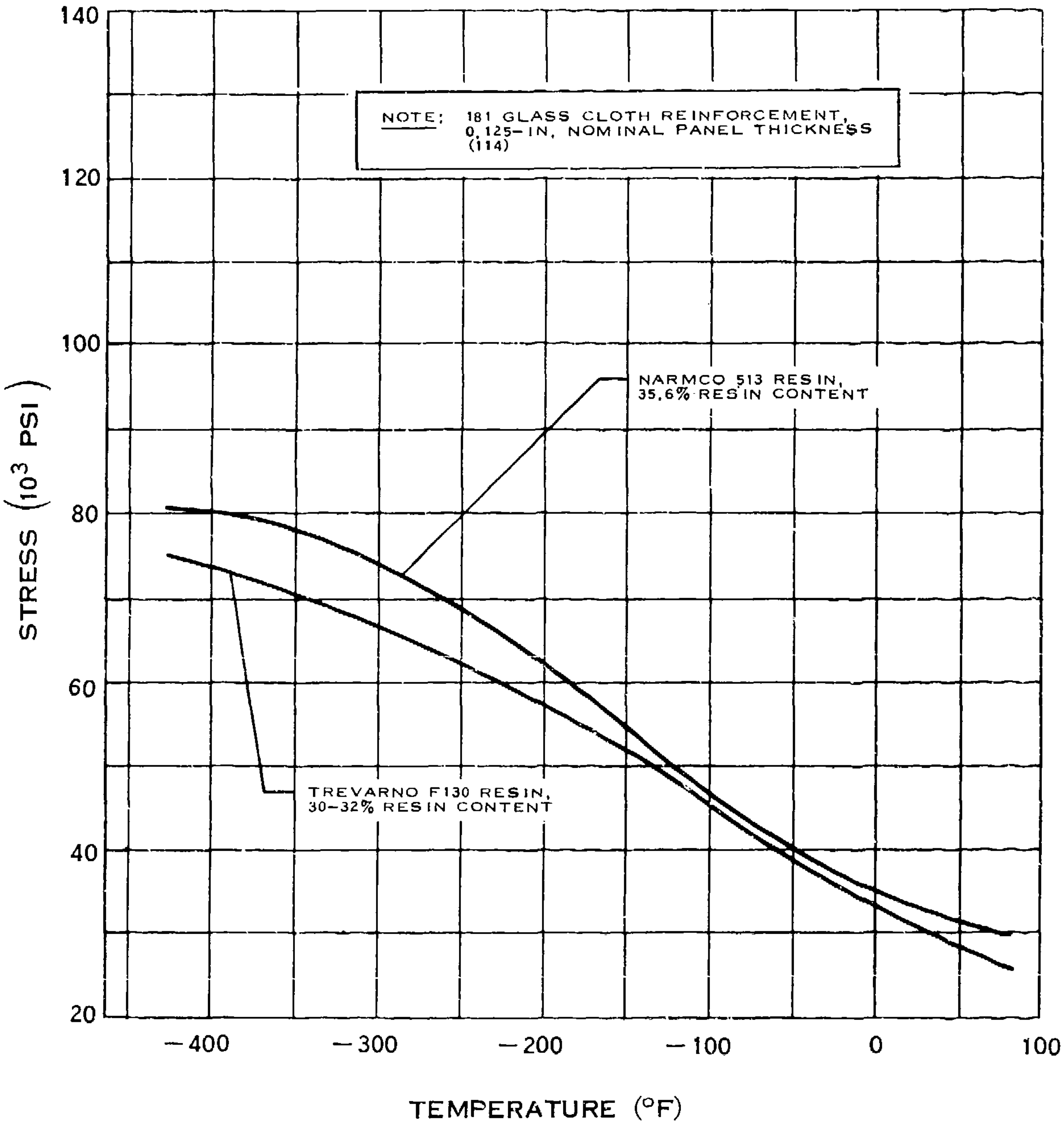
(6-68)

H.4.v



THERMAL CONDUCTIVITY OF POLYESTER-FIBERGLAS LAMINATE

(6-68)



TENSILE STRENGTH OF SILICONE - FIBERGLAS LAMINATE

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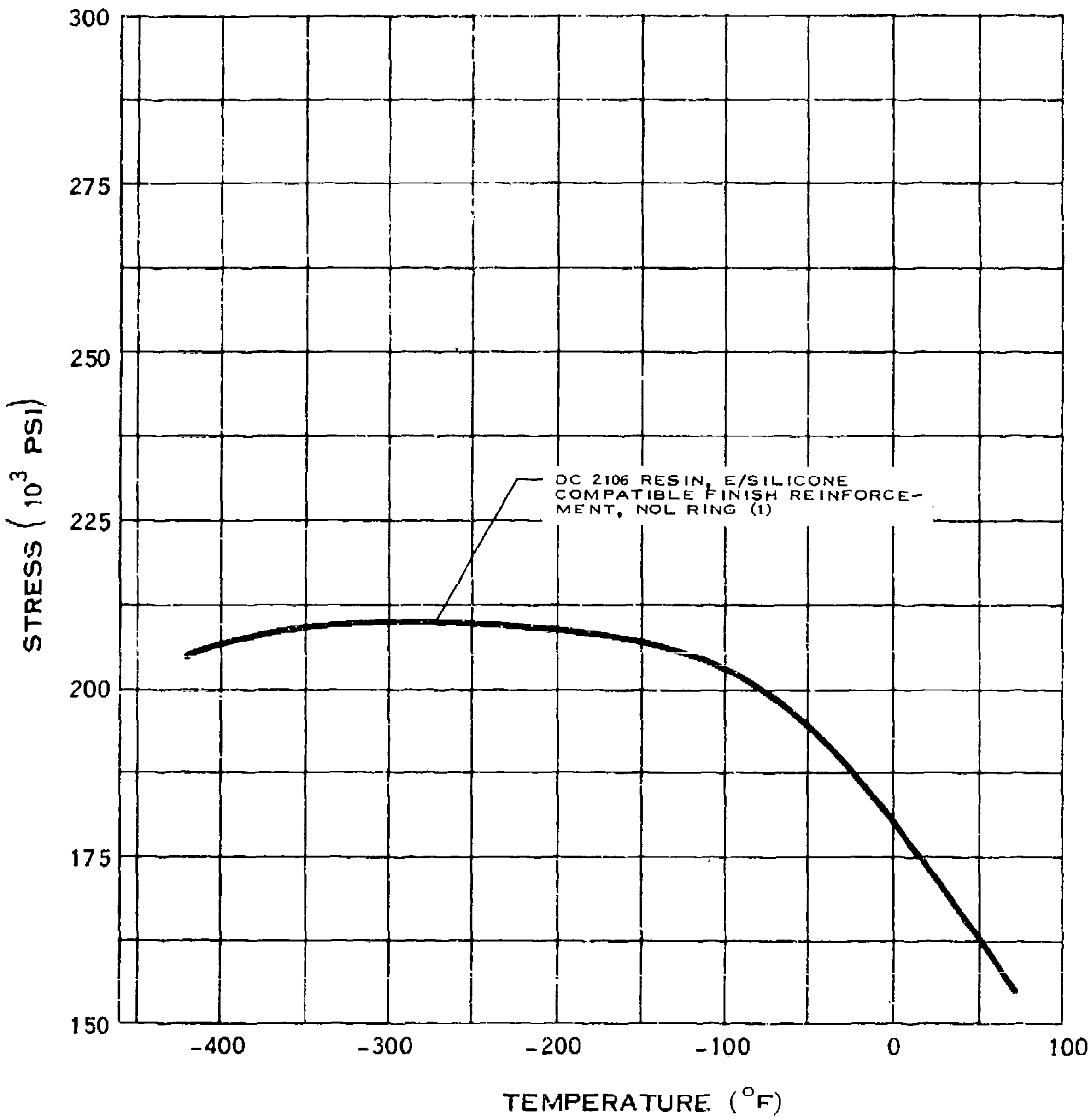
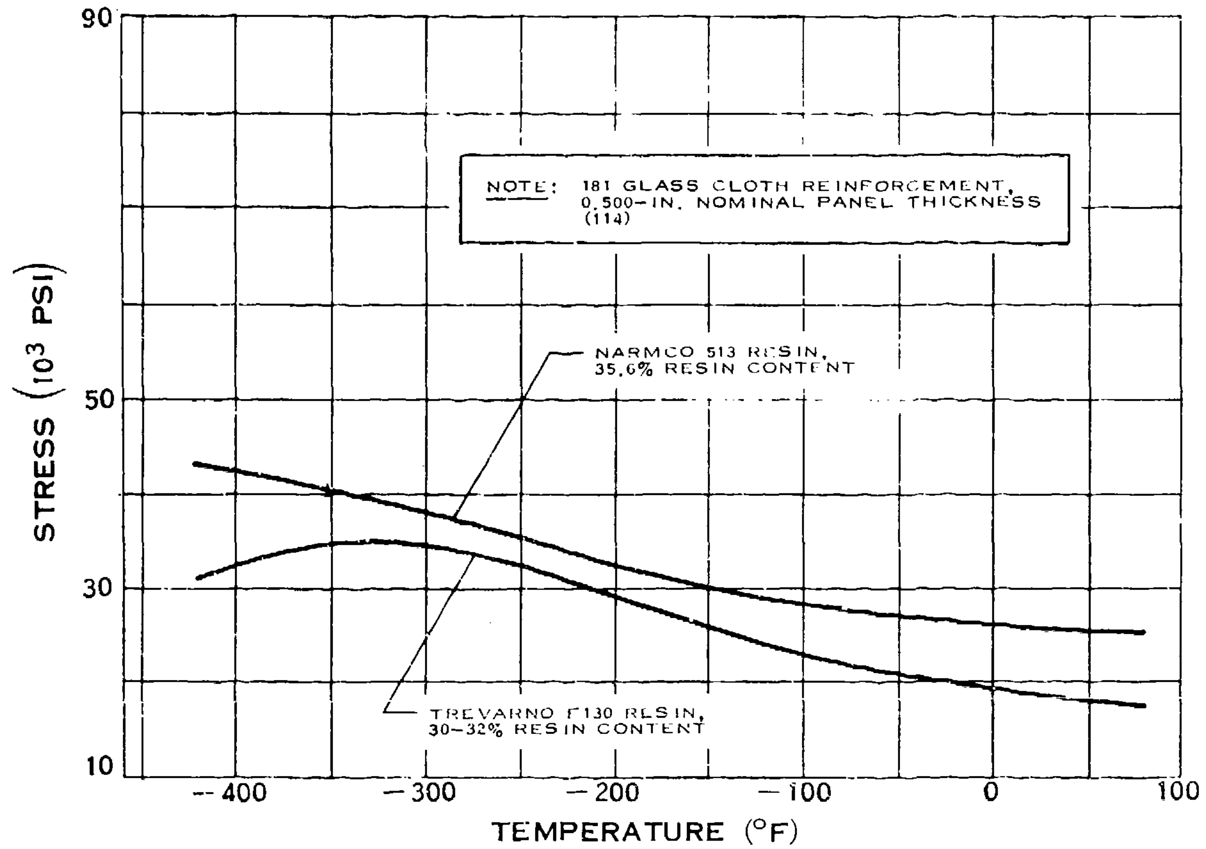


TENSILE STRENGTH OF SILICONE-FIBERGLAS FILAMENT WOUND RINGS

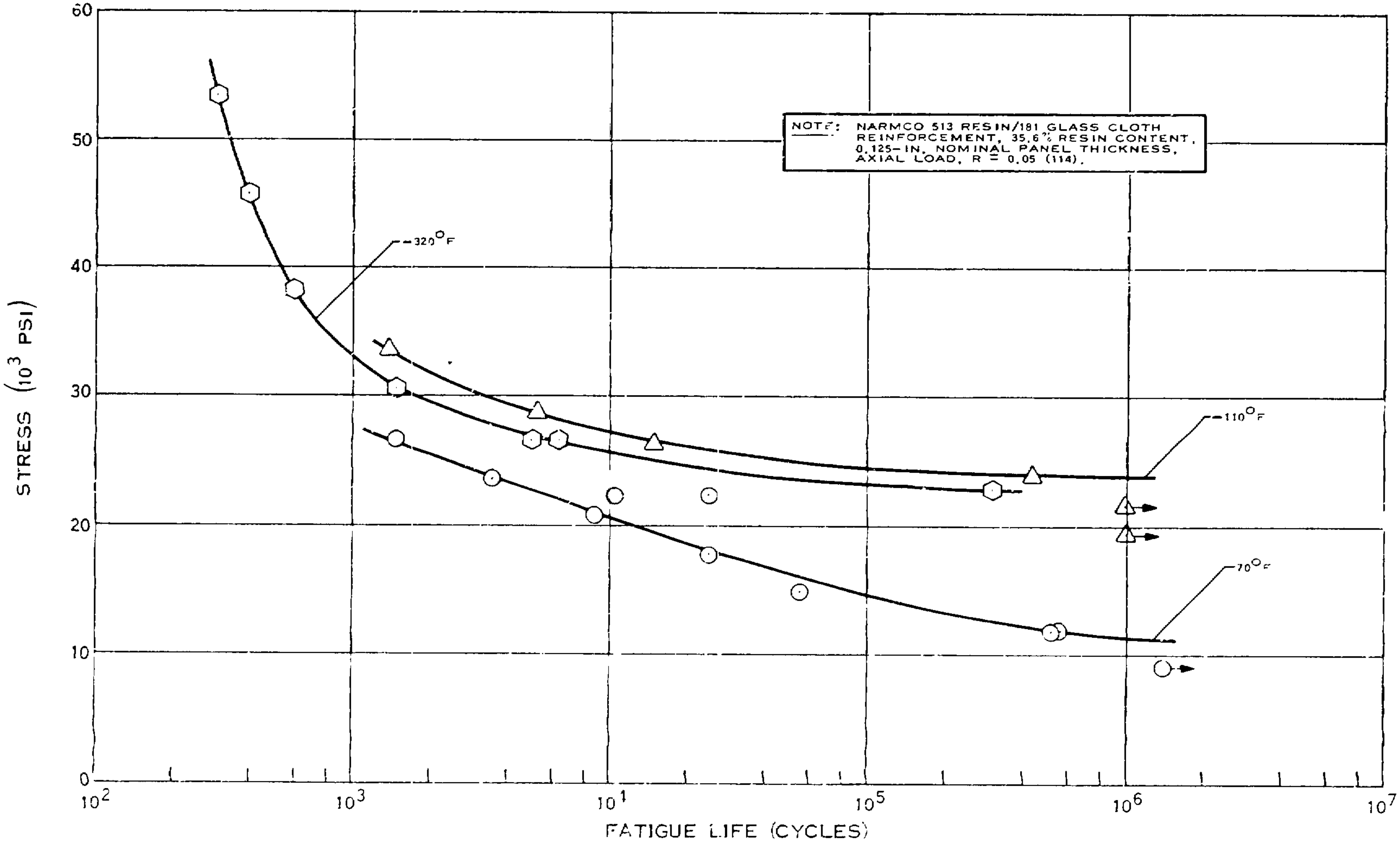
(1-65)

H.5.m

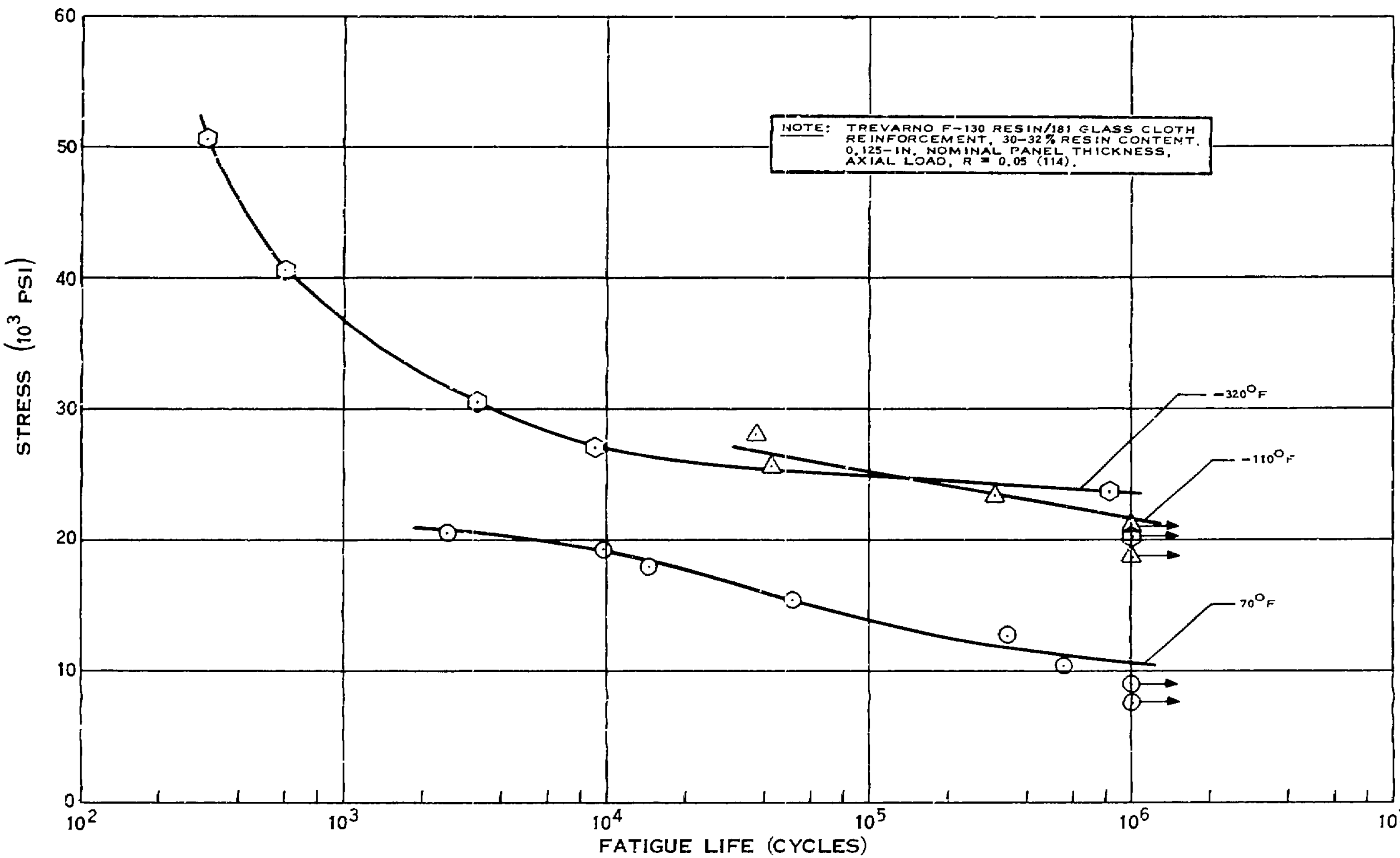


COMPRESSIVE STRENGTH OF SILICONE - FIBERGLAS LAMINATE

(1-65)

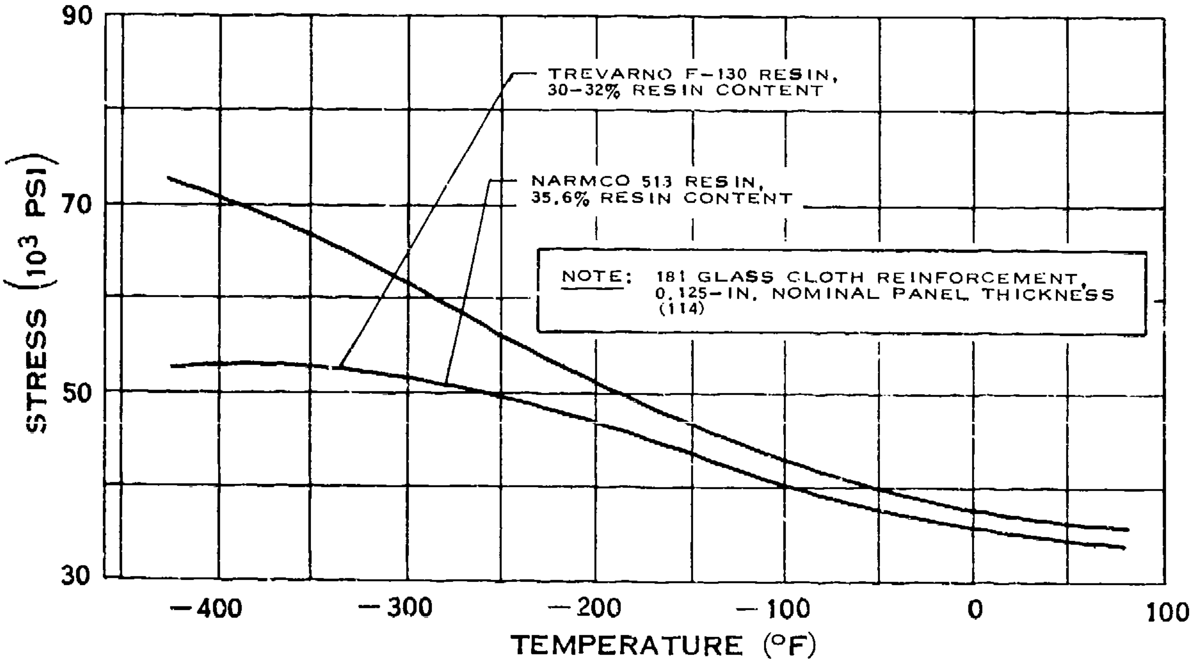


FATIGUE STRENGTH OF SILICONE-FIBERGLAS LAMINATE

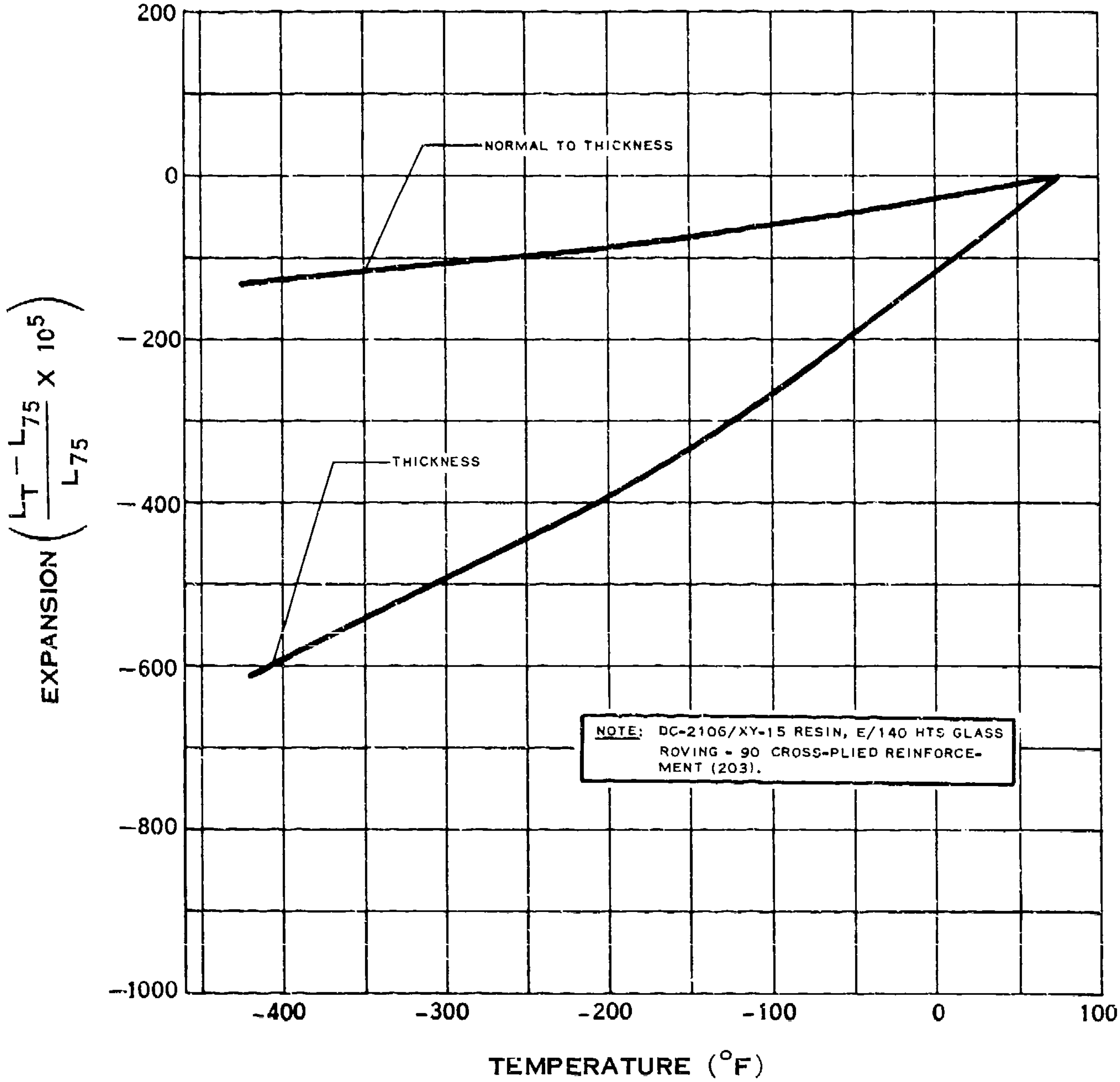


FATIGUE STRENGTH OF SILICONE-FIBERGLAS LAMINATE

H.5.r



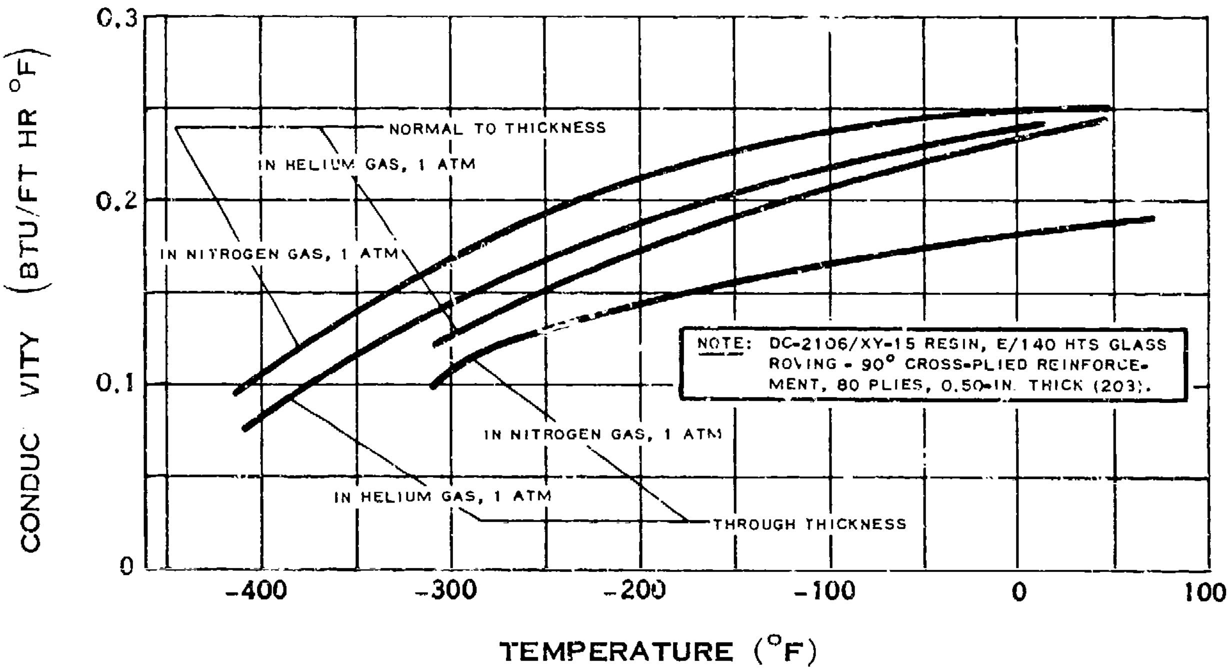
FLEXURAL STRENGTH OF SILICONE - FIBERGLAS LAMINATE



THERMAL EXPANSION OF SILICONE-FIBERGLAS LAMINATE

(6-68)

H.5.v



THERMAL CONDUCTIVITY OF SILICONE-FIBERGLAS LAMINATE

(6-68)

H.6

See the following graphs for properties of Reirforced Teflon.

G.3.a-2

G.3.a-3

G.3.a-4

G.3.b-3

G.3.b-5

G.3.c-3

G.3.c-4

G.3.i-2

G.3.i-3

G.3.j-1

G.3.j-2

G.3.ℓ-2

G.3.ℓ-3

G.3.m-3

G.3.m-4

G.3.m-5

G.s.n-2

G.3.n-3

G.3.n-4

G.3.r-2

G.3.s-2

G.3.t

G.3.t-2

G.3.t-3

G.3.t-4

G.3.t-5

G.3.t-6

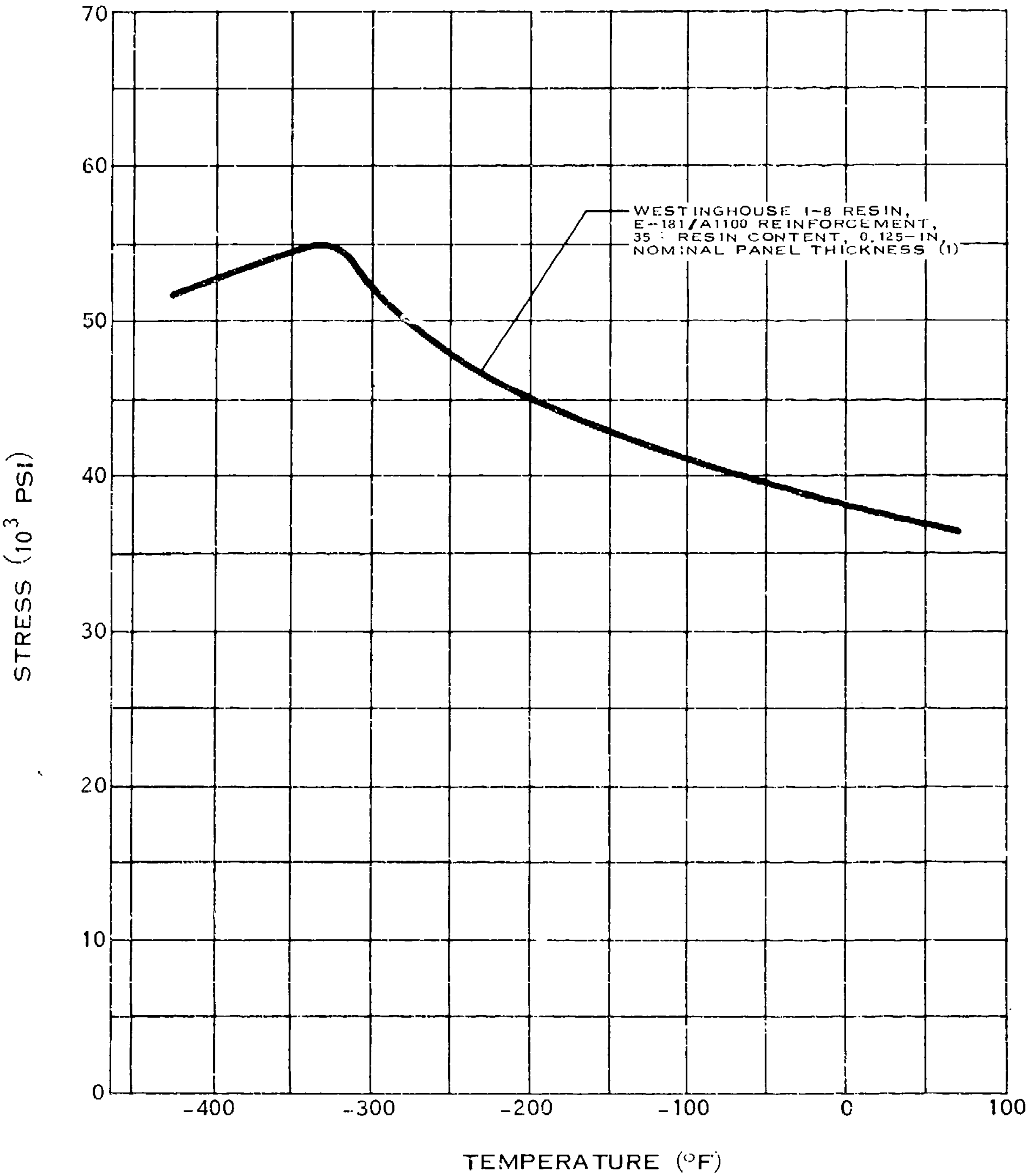
G.3.v

G.3.v-1

G.3.v-2

(6-68)

H.7.b



TENSILE STRENGTH OF POLYIMIDE FIBERGLAS LAMINATE

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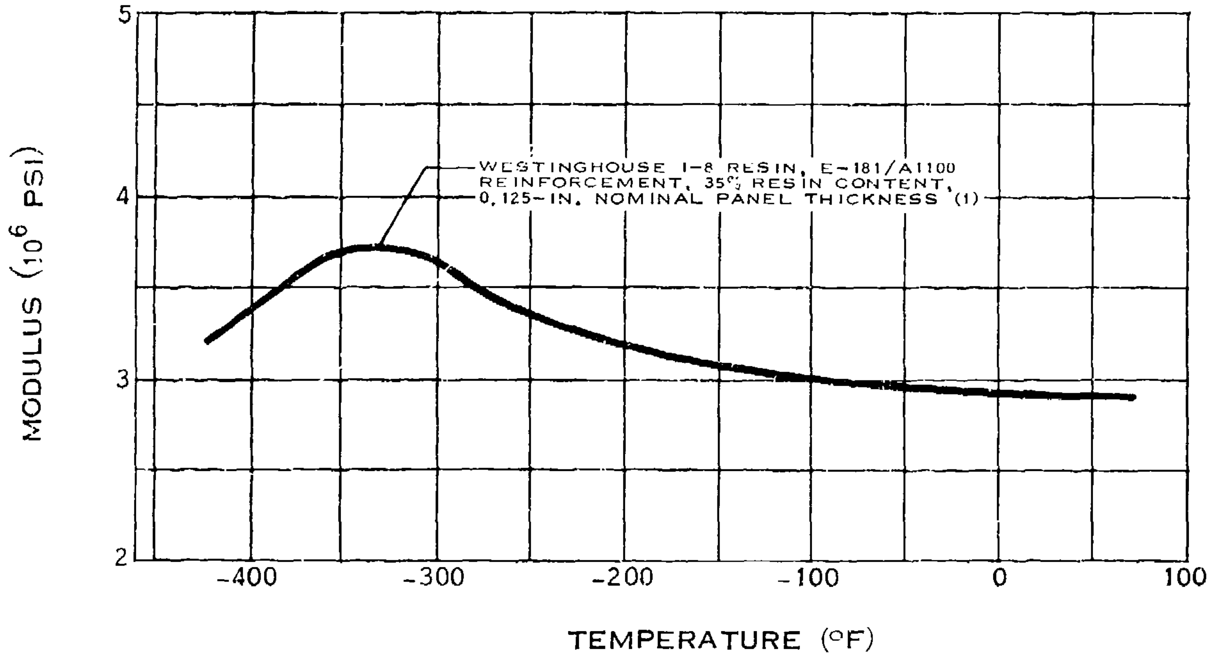
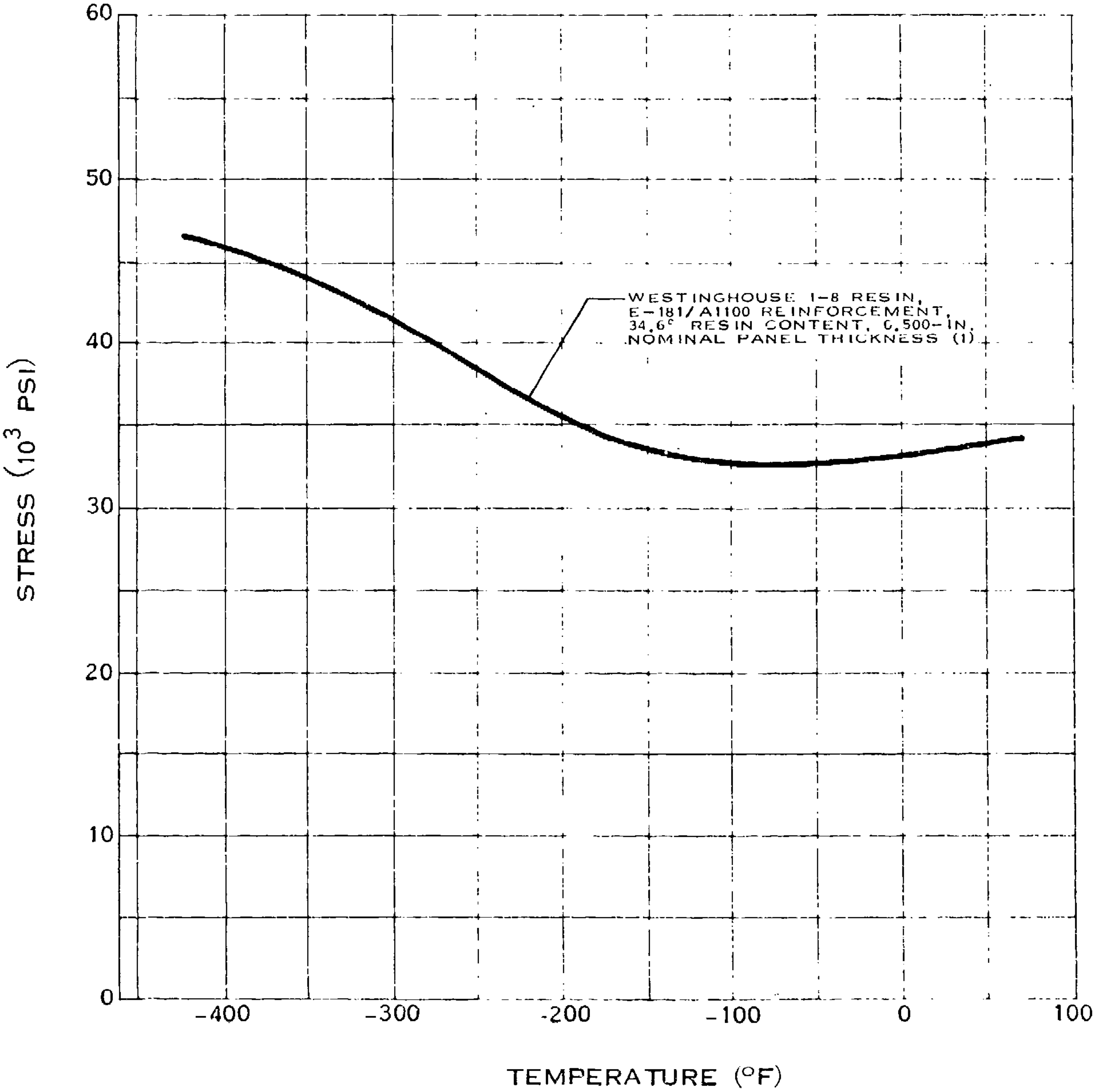
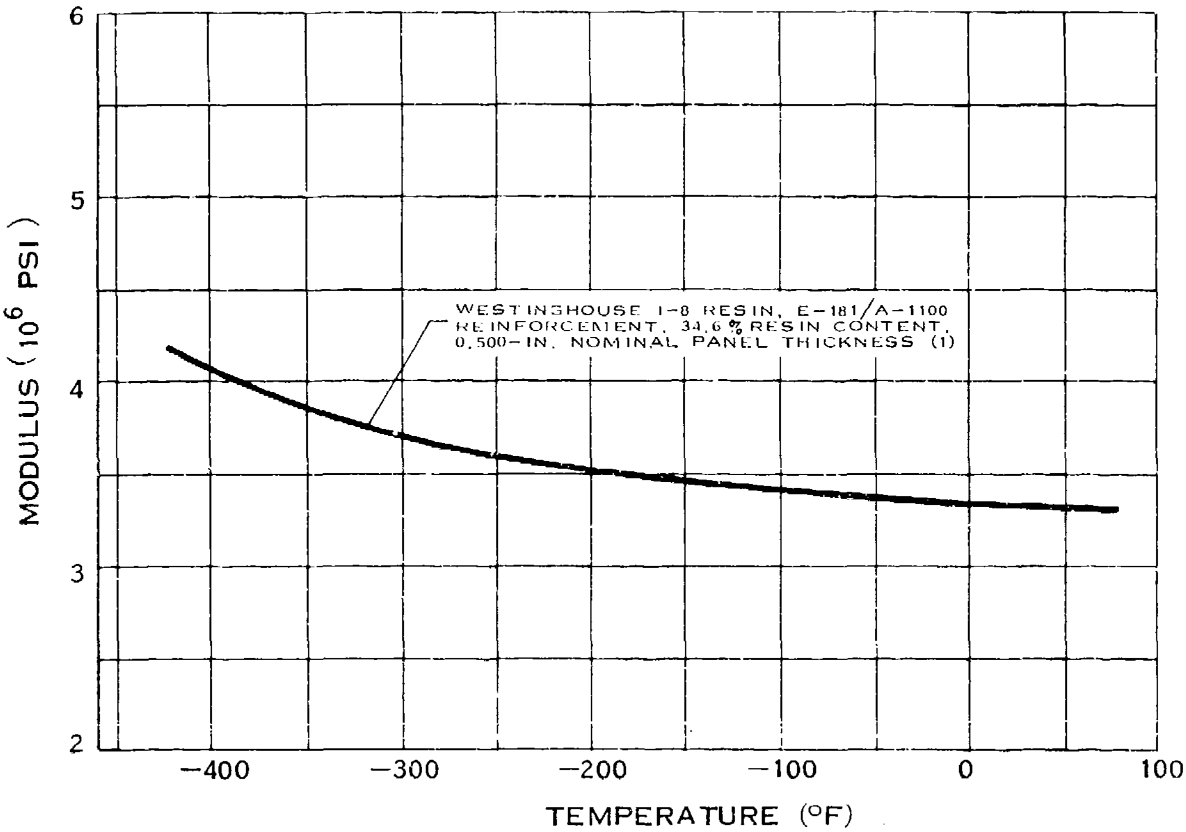
H.7.i



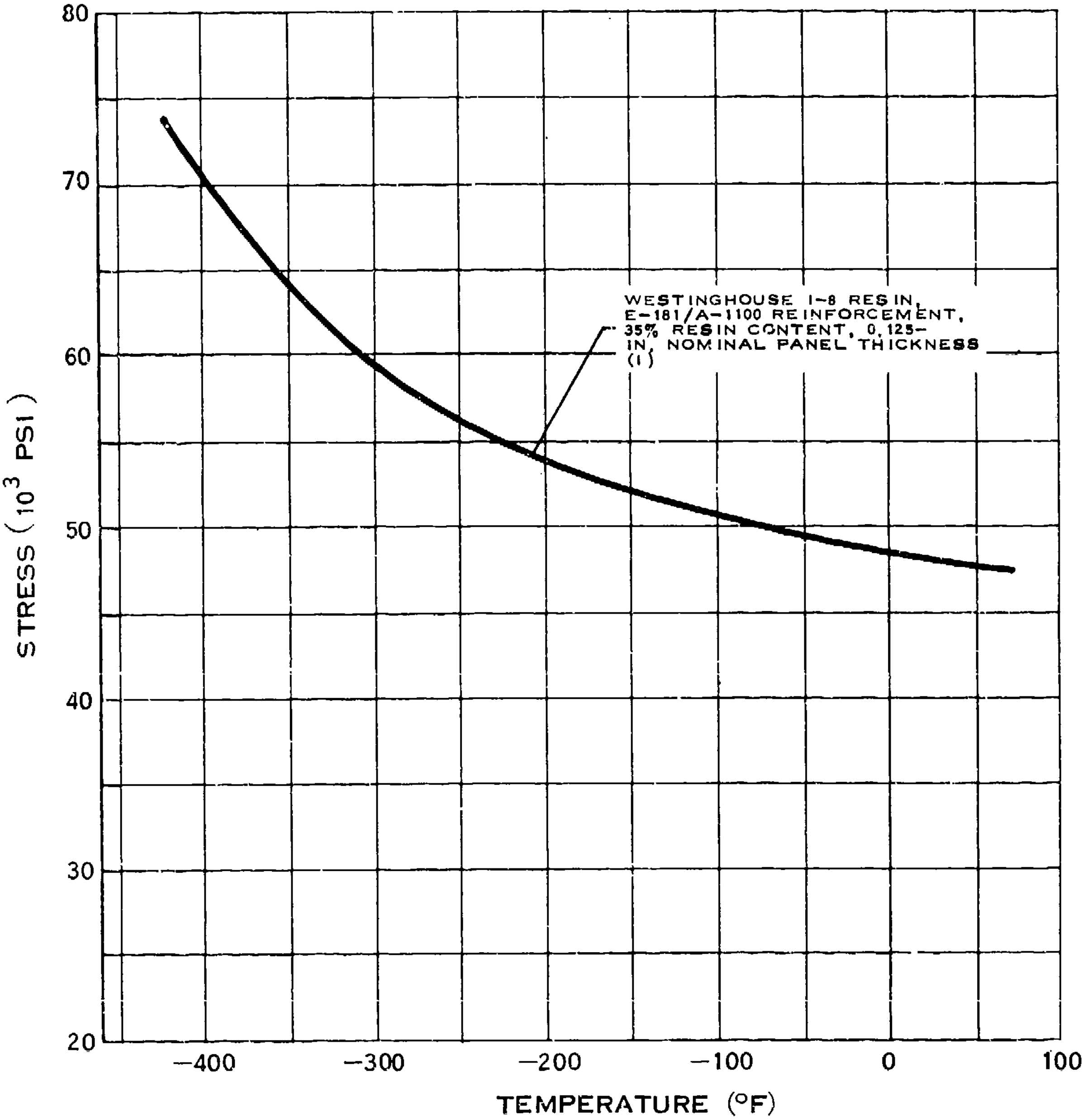
MODULUS OF ELASTICITY OF POLYIMIDE-FIBERGLAS LAMINATE



COMPRESSIVE STRENGTH OF POLYIMIDE-FIBERGLAS LAMINATE



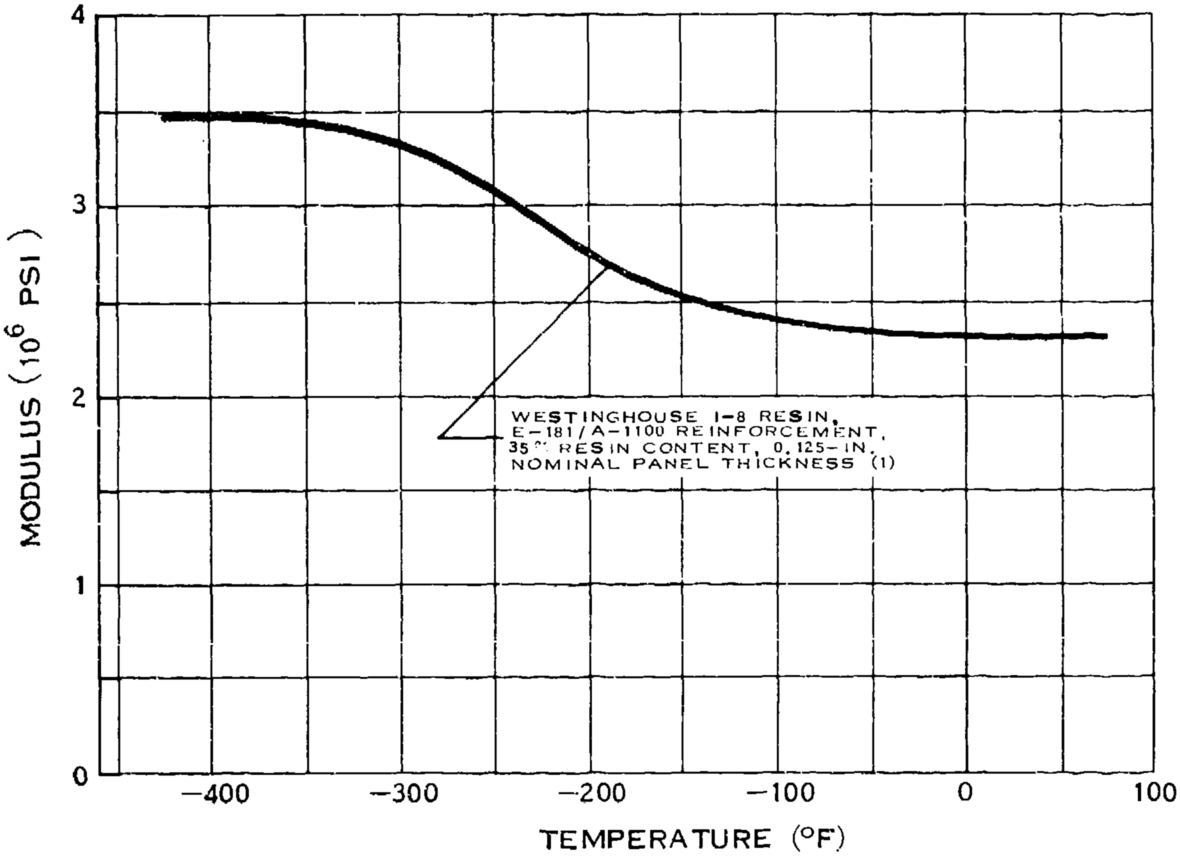
COMPRESSIVE MODULUS OF POLYIMIDE-FIBERGLAS LAMINATE



FLEXURAL STRENGTH OF POLYIMIDE-FIBERGLAS LAMINATE

(1-65)

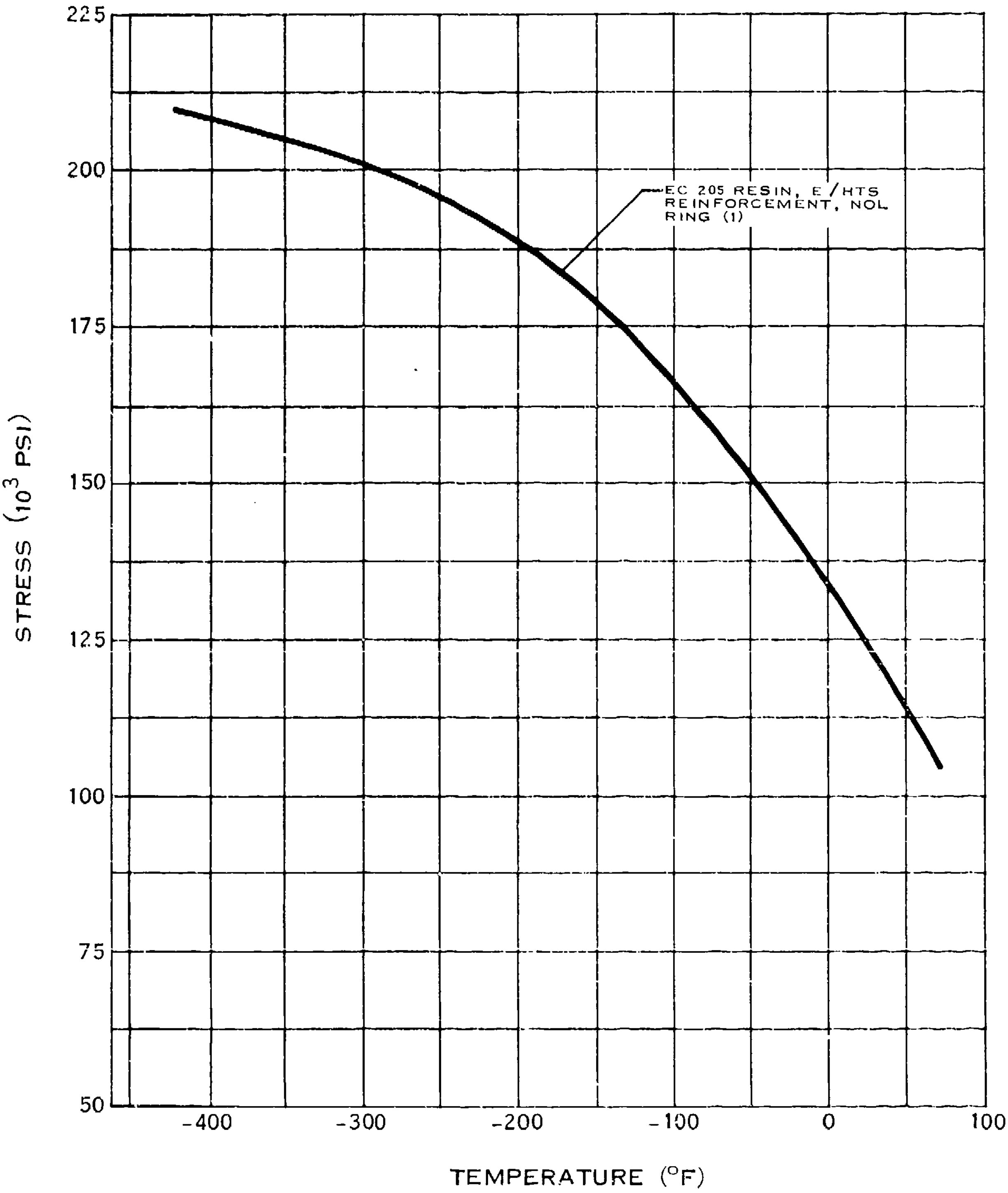
H.7.s



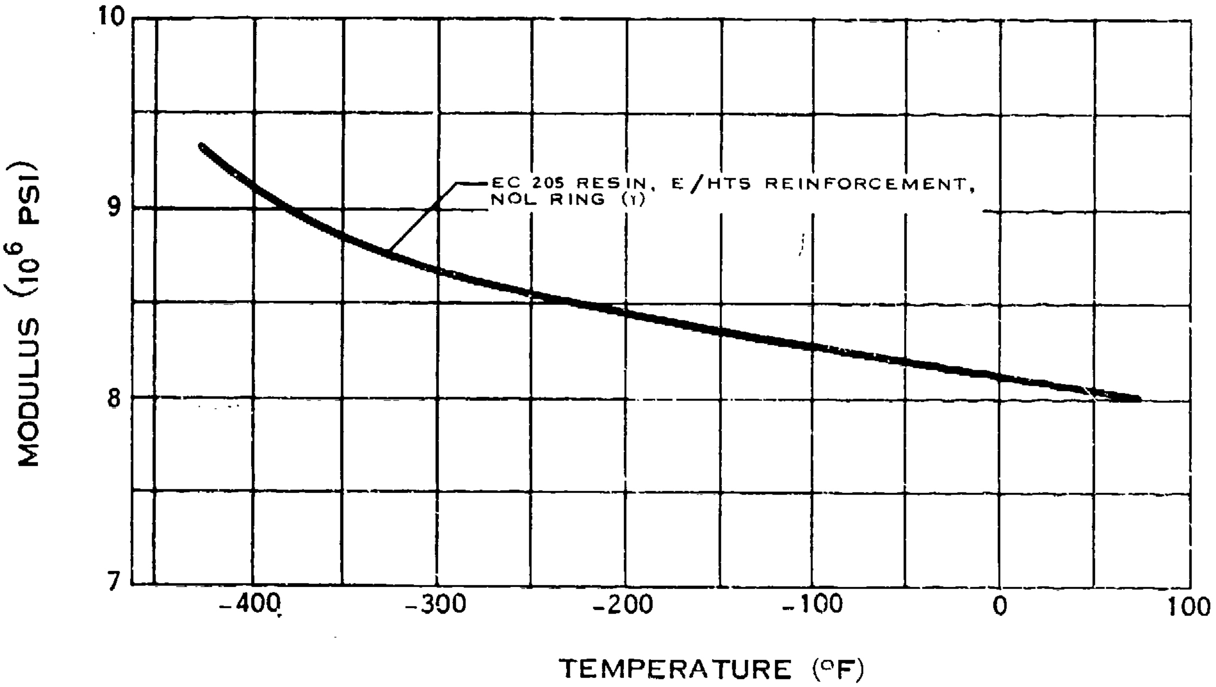
FLEXURAL MODULUS OF POLYIMIDE-FIBERGLAS LAMINATE

(1-65)

H.8.b

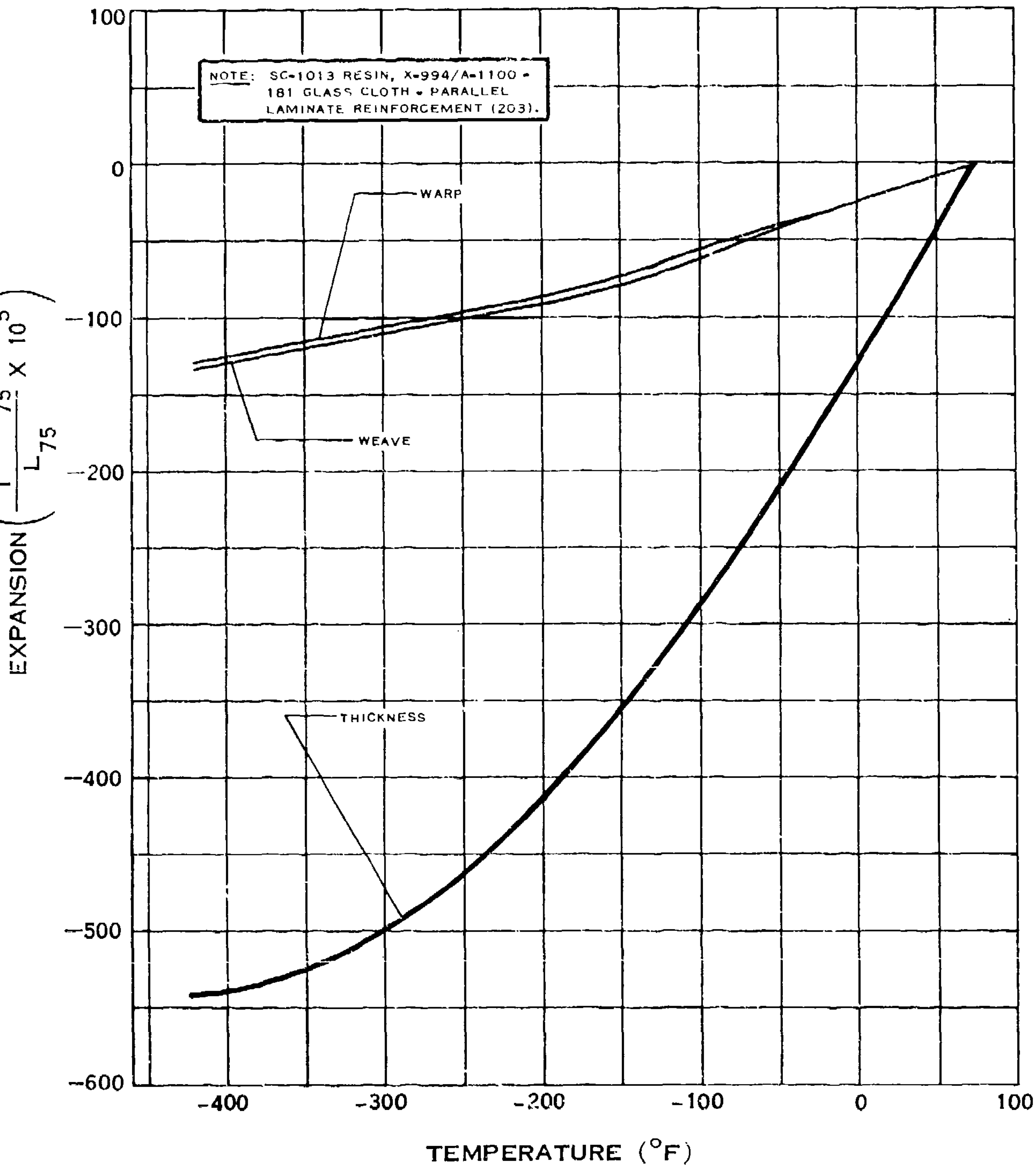


TENSILE STRENGTH OF PHENYL-SILANE FIBERGLAS FILAMENT WOUND RINGS



MODULUS OF ELASTICITY OF PHENYL-SILANE FIBERGLAS FILAMENT WOUND RINGS

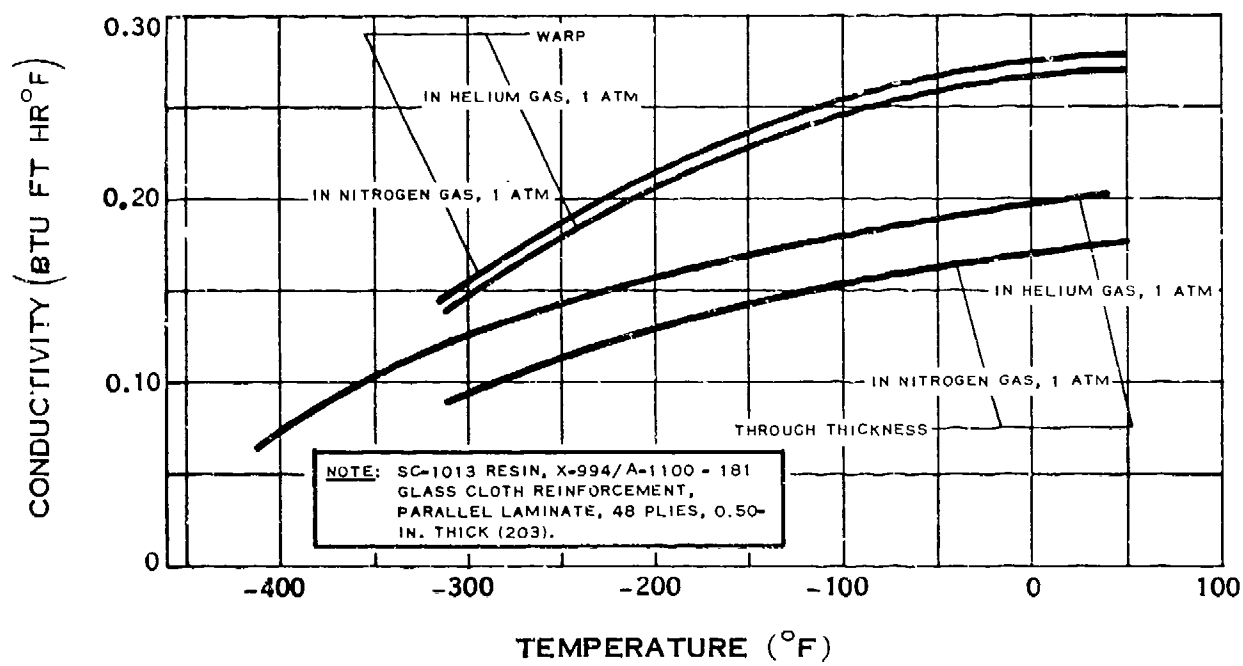
(1-65)



THERMAL EXPANSION OF PHENOLIC-SILANE-FIBERGLAS LAMINATE

(6-68)

H.8.v



THERMAL CONDUCTIVITY OF PHENYL SILANE-FIBERGLAS LAMINATE

(6-68)

I-MISCELLANEOUS

NON-METALLICS

NON-METALLIC MATERIALS FOR SEALS AND GASKETS

A. INTRODUCTION

In the billion dollar cryogenic industry, there is no more important single component than the cryogenic seal. It has been estimated that 40% of the $5 billion NASA program depends on cryogenics, and every transfer of liquid hydrogen, nitrogen, or oxygen in testing, liftoff, or flight depends on faultless performance of valves and static seals. This review of the use of non-metallics in cryogenic seals is intended to give the reader a brief look at some successful solutions to seal problems. The articles in the bibliography following the text are chosen to cover the subject in more detail.

Important related subjects that deserve more attention in the future are leak rate characterization, flange design, and compatibility testing. Some subjects that are not discussed are static metallic seals, welded or brazed joints, adhesives, and sealants. A main contribution to the bibliography is a literature search performed by the Cryogenic Data Center, Cryogenics Division, Institute for Basic Standards, National Bureau of Standards.

B. NON-METALLIC GASKETS

For a number of reasons variations of polytetrafluoroethylene (PEFE) dominate the subject of non-metallic gaskets for cryogenic service. One important reason is compatibility with oxygen. Most non-metallics will react with oxygen if subjected to an impact energy of 70 ft-lb. However, PTFE is compatible with oxygen, and therefore is useful in liquid oxygen transfer systems. Virgin PTFE and other unmodified fluorocarbons have the undesirable property of cold flow. That is, irreversible plastic deformation occurs when a constant load is applied for a period of time. To counteract cold flow and still maintain a soft, high-performance seal surface, the designs of Fig. I-1 have been used. Figure I-1(a) shows a gasket cross section in which PTFE has been filled with particles or fibers (usually glass), which add strength, reduce thermal contraction, and inhibit cold flow. Such gaskets are usually quite hard, and require high flange loads and serrated flange faces. The logical improvement is to design a composite gasket, with a PTFE (or fluorinated ethylene propylene, FEP) coating to provide a soft sealing surface and an interior designed to stop cold flow.

(6-68)

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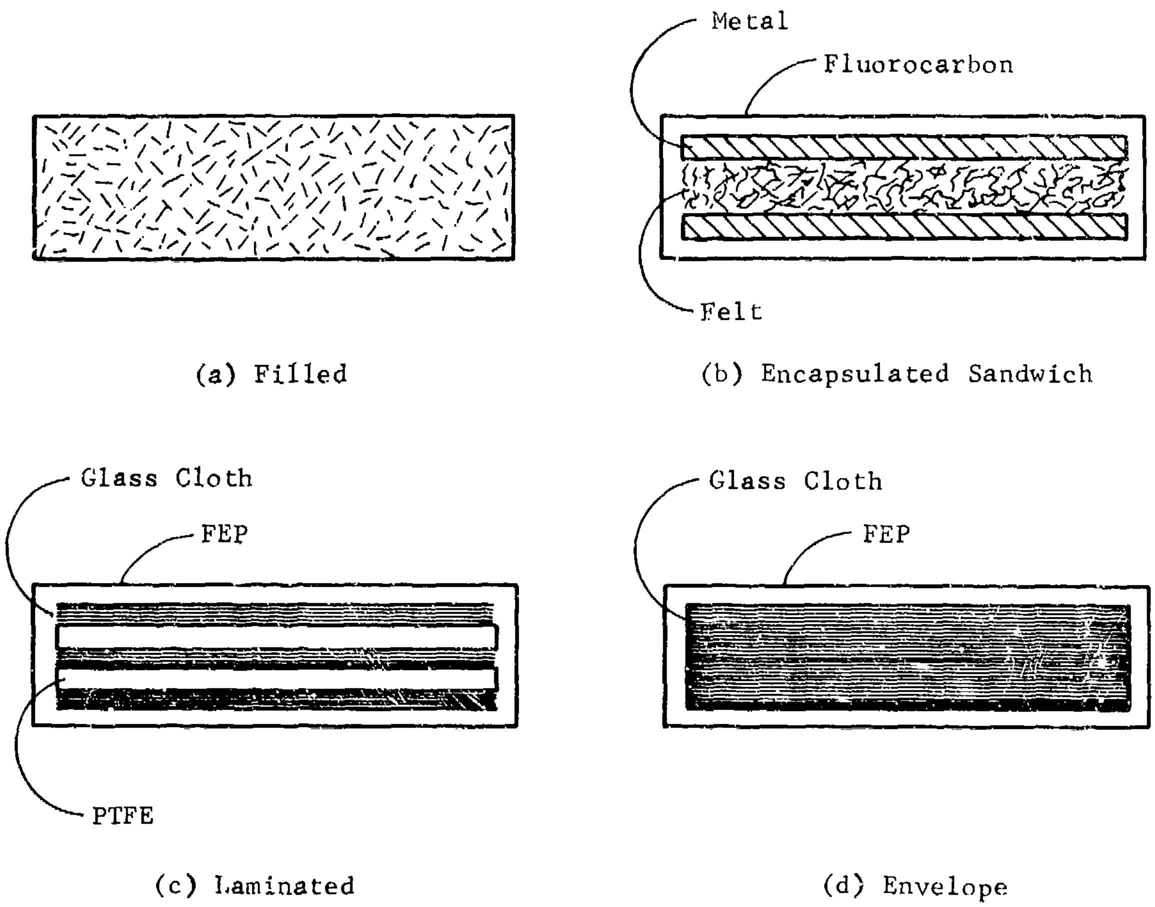

Figure I-1 Fluorocarbon Polymer Gasket Cross Sections

Three such designs are shown in Fig. I-1(b), (c), and (d). In Fig. I-1(b) a felt pad is sandwiched between thin metal sheets. This combination forms a spring-like core, which is encapsulated in FEP or PTFE. In Fig. I-1(c) the core is alternating layers of PTFE and glass cloth. The laminate is bonded by heat and pressure, but the PTFE is not allowed to completely impregnate the cloth. This treatment results in a reasonably solid core that retains some low temperature elasticity. Figure I-1(d) shows the "envelope" gasket developed during the same program as the laminated gasket. The gasket is made by encapsulating multiple layers of glass fabric in FEP film.

Although individual material properties are important, the bulk properties of gaskets such as those in Fig. I-1 are more readily related to seal performance. Gasket materials investigated in the program that resulted in the composites shown in Fig. I-1(c) and (d) were subjected to compression tests in a standard testing machine. The area under the load-deflection curves was taken as a measure of the energy absorption capabilities of the gasket.

(6-68)

Another polymer that has been used successfully for cryogenic gaskets is the thermoplastic polyethylene terephthalate (PETP). This is a high modulus film material that requires high compressive stress to cause plastic deformation at the seal flange interface. Consequently one of the mating flanges is usually machined with a ring of about 3/16-inch radius protruding from the face. The height of the ring is 70 to 80% of the gasket thickness. High-vacuum low-temperature seals of 0.010-inch-thich PETP have been made in several cryogenic laboratories, and by at least one manufacturer of cryogenic hardware, using this flane design. Unfortunately PETP is not compatible with oxygen.

C. NON-METALLIC O-RINGS

The simplicity, reliability, and long service life of rubber O-rings has led to a wide variety of uses at temperatures in the rubbery region. Unfortunately, all elastomers become hard and glassy at temperatures well above the boiling point of cryogens, and they cannot be used for cryogenic seals in the conventional manner.

Two interesting designs which have enabled rubber O-rings to perform well at low temperatures are shown in Fig. I-2. In the "step flange" configuration of Fig. I-2(a), the O-ring is compressed to a thin, L-shaped cross section that produces high stress in the corner. O-rings made from elastomers that have high elongation and yield strength at room temperature (natural rubber and neoprene, for instance) will not fail when subjected to this type of compression. When the compressed O-ring is cooled below the glass transition, it maintains a high vacuum seal in spite of the change in properties if the step flanges are designed properly. In another related design, Fig. I-2(b), the O-ring is stretched on a metal insert ring and compressed between two flat flanges. This design depends on some spring loading in the flanges as well as high stress concentration to prevent leakage below the glass transition.

PTFE rings with an 0.1-inch square cross section have been used successfully in cryogenic research cryostats. The rings is designed to shrink-fit into a groove in one flange, with a small amount of the ring projecting out of the groove to seal against the mating flange. If this seal is to perform adequately, the flanges must be carefully finished to avoid small scratches across the rather narrow seal interface.

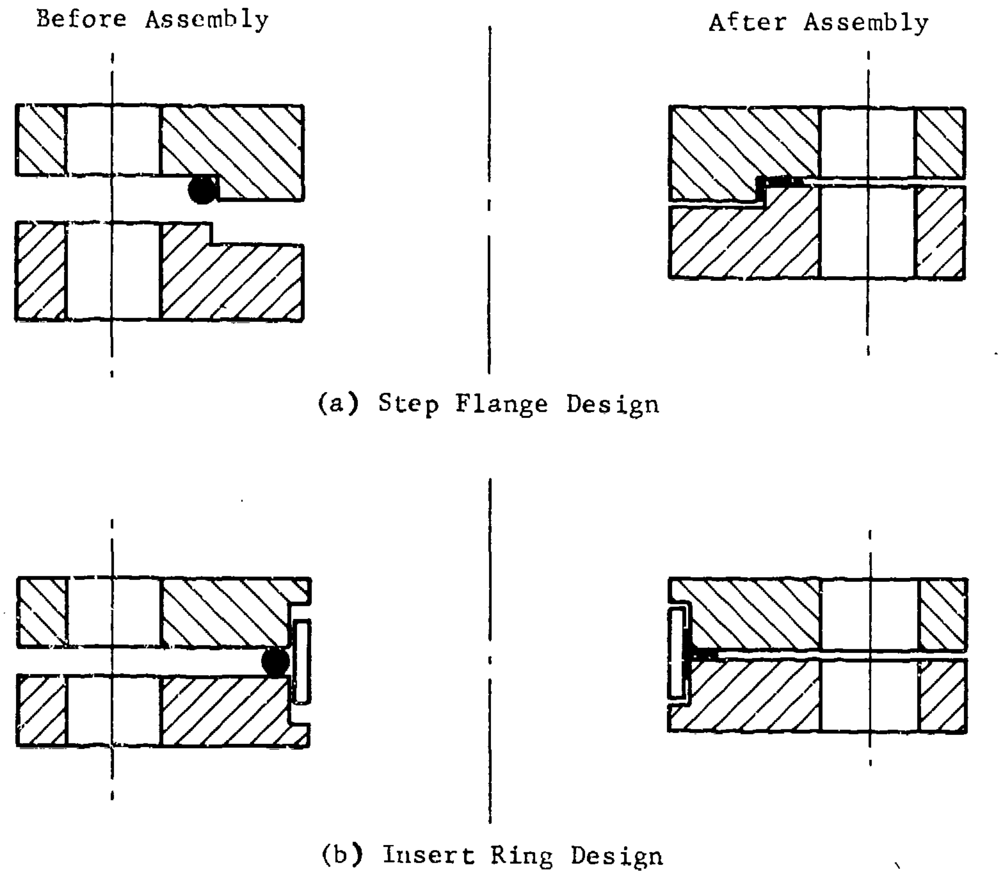

Fig. I-2 Elastomeric O-Ring Designs

D. PRESSURE-ACTUATED SEALS

A class of pressure-actuated seals has found wide acceptance in recent years. The spring-like metal bodies are usually coated with a non-metallic such as PTFE, FEP, or polychlorotrifluoroethylene (PCTFE). The gaskets and O-rings discussed previously would not meet the space age requirement of high flange deflection capability; hence the development of this class of expensive cryogenic seals. Figure I-3 shows some of the cross sections in use today.

Careful calculations based on the yield strengths of the metal body and the non-metallic coating are necessary prerequisites to pressure-actuated seal design, and the flange surfaces must be polished to a degree not necessary with O-ring gaskets. In all cases the system pressure is used to increase the sealing force.

(6-68)

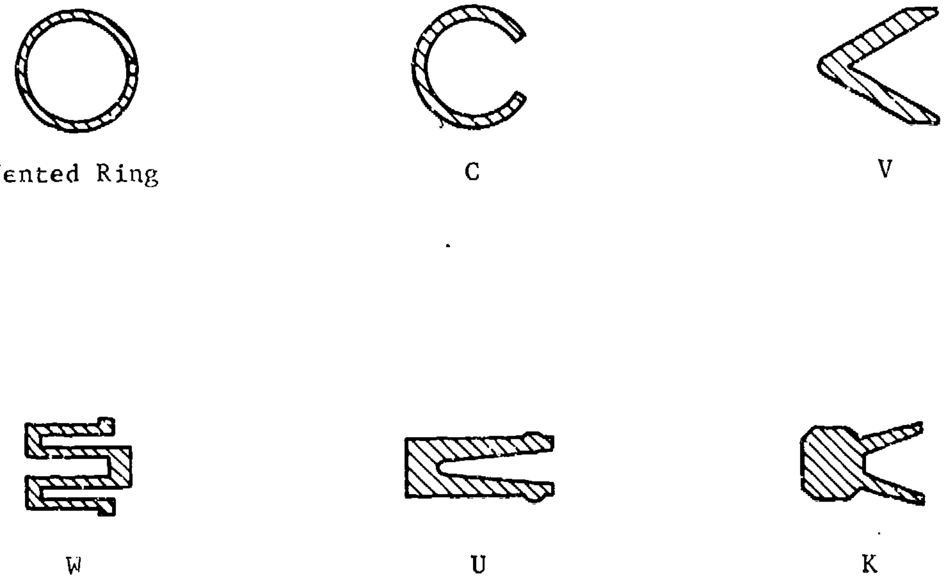

Fig. I-3 Pressure-Actuated Seal Cross Sections

Careful calculations based on the yield strengths of the metal body and the non-metallic coating are necessary prerequisites to pressure-actuated seal design, and the flange surfaces must be polished to a degree not necessary with O-ring gaskets. In all cases the system pressure is used to increase the seal force.

Much development work is still being done on pressure-actuated seals, because designers faced with the requirements of lightweight flanges and high deflection at low temperatures usually specify this type of seal. There are at least a dozen commercial suppliers of variations of the designs shown in Fig. I-3, but very little information on pressure-actuated seals has been published in the open literature.

E. DYNAMIC SEALS

Non-metallics are used extensively in applications such as rotating face and shaft seals, valve seats, and lip seals. Because of the low coefficient of friction, the fluorocarbon polymers mentioned previouly are generally chosen for the seal material.

PTFE filled with molybdenum disulfide is a popular non-metallic material for use in rotating face seals. Unfilled PCTFE is used extensively in lip seals, and PTFE seats are common in cryogenic valves. Most of the information on dynamic seals must be obtained from the manufacturers.

F. BIBLIOGRAPHY

The following 37 articles were selected for their pertinence to the design of non-metallic seals for cryogenic service. Notice that there are no references listed describing pressure-actuated seals; data on these are available only from the suppliers. For a listing of some manufacturers of pressure-actuated seals see Robbins and Ludtke.*

1. General

Ashmead, R. H.: "Static Seals for Missile Applications." Jet Propulsion. Vol 25 (1955).

Bauer, P., Glickman, M., and Iwatsuki, F.: Analytical Techniques For the Design of Seals For Use in Rocket Propulsion Systems, Volume I, Static Seals. AFRPL-TR-65-61, Vol 1 (May 1965).

Bauer, P., Glickman, M., and Iwatsuki, F.: Analytical Techniques For the Design of Seals for Use in Rocket Propulsion Systems, Volume II, Dynamic Seals. AFRPL-TR-65-61, Vol 2 (May 1965).

Cleland, E., Harrington, R., and Maxwell, H.: Polymers For Spacecraft Hardware. Materials Characterization, Part I. NASA-CR-81377 (December 1966).

Elwell, R. C. and Bialous, A. J.: Study of Dynamic and Static Seals for Liquid Rocket Engines, Vol 1 Description of Program and Results of Evaluation of Available Sealing Methods. Final Report, General Electric Co. (NASA Contract NAS7-102) (1963).

George, R. L. and Elwell, R. C.: Study of Dynamic and Static Seals for Liquid Rocket Engines. Vol 3B. Bibliography of Open Literature on Seals. Final Report, General Electric Co. (NASA Contract NAS7-102), March 29, 1963.

*"Review of Static Seals for Cryogenic System." J. Spacecraft and Rockets, 1, No. 2, 253-9 (1964).

George, R. L., and Elwell, R. C.: Study of Dynamic and Static Seals for Liquid Rocket Engines. Vol 3A. Bibliography of ASTIA Literature on Seals. Final Report, General Electric Co. (NASA Contract NAS7-102), March 29, 1963.

Landrock, A. H.: Properties of Plastics and Related Materials at Cryogenic Temperatures. Plastic Report. No. 20. Plastics Tech. Eval. Center, Picatinny Arsenal, Dover, N. J. (July 1965).

Mauri, R. E.: "Materials For Sealing Applications." Space Materials Handbook (C. G. Goetzel et al. editors). 321-66, Addison-Wesley Publishing Co., Inc. (1965).

Perkins, R. B. and Glarum, S. N.: Adhesives, Sealants, and Gaskets--A Survey. NASA-SP-5066. NASA N67-16060 (1967).

Rathbun, F. O., Jr.: Design Criteria For Zero Leakage Connectors For Launch Vehicles. NASA CR-56571 (June 1964). NASA N64-27305.

Rittenhouse, J. B. and Singletary, J. B.: Space Materials Handbook, Supplement I to the Second Edition. 3025, ML-TDR-64-40 Suppl 1. (1966), DDC AD 629 720.

Robbins, R. F. and Ludtke, P. R.: "Review of Static Seals For Cryogenic Systems." J. Spacecraft & Rockets 1, No. 2, 253-9 (1964).

2. Non-Metallic Gaskets

Astrov, D. N. and Belyanskii, L. B.: "A High-Vacuum Seal For Low Temperatures." Instr. Exptl. Tech. (USSR), No. 2, 506 (Mar-Apr 1966).

Burt, S. L., Stuckey, J. M., and Thompson, L. M.: Aging of Installed Rubber and Plastic Gaskets in Simulated Flight Hardware. NASA TM X-54517 (1962).

Curry, J. E. and Scheck, W. G.: "The Development of a New Cryogenic Gasket For Liquid Oxygen Service." Proc. of the Conf. on the Design of Leak-Tight Fluid Connectors. 117-28 (Aug 1965).

Gosnell, R. B.: "The Development of a New Cryogenic Gasket For Liquid Oxygen Service." Advances in Cryogenic Engineering. Vol 9 (K. D. Timmerhaus, ed.), Plenum Press, N. Y. (1964).

Marano, D. and Sheck, W. G.: Development of Improved Lox Compatible Laminated Gasket Composite. NASA-CR-79703 (Aug 1966).

Roseland, L. M., Jr.: Composite Material For Cryogenic Usage." Cryogenic Technol. Vol 2, No. 1, 23-5 (June 1966).

Turner, H. S.: "Gaskets For High Vacuum." Prod. Eng. Vol 37, No. 3, 62-66 (Jan 1966).

3. Non-Metallic O-Rings

Farkas, I. and Barry, E. J.: "Improved Elastomer Seal Designs For Large Metal Ultra-high Vacuum Systems Permitting Ultimate Pressures in the Low 10^{-10} Torr Range." Trans. 7th Vacuum Symp. pp. 35-38, Permagon Press, N. Y. (1961).

Herring, R. N.: "Elastomer O-ring Seals For Static Applications at Low Temperatures." Masters Thesis, Colorado University, Dept. Chemical Engineering (1962).

"O-Rings With Mylar Back-Up Provide High-Pressure Cryogenic Seal." National Aeronautics and Space Administration, Washington, D. C., Tech. Brief B66-10278 (June 1966).

Pickett, A. G. and Lemcoe, M. M.: Handbook of Design Data on Elastomeric Materials Used in Aerospace Systems. TR 61-234. Aeronautical Systems Div., Air Force Systems Command ASTIA AD No. 273880 (January 1962).

Weitzel, D. H.: Pipe Coupling. U. S. Patent 3,339,948 (Sept 1967).

Weitzel, D. H., Robbins, R. F., Bopp, G. R., and Bjorklund, W. R.: "Elastomers For Static Seals at Cryogenic Temperatures." Advances in Cryogenic Engineering. (edited by K. D. Timmerhaus) Plenum Press, Inc., New York, 1961, Vol 6 pp 219-227.

Weitzel, D. H., Robbins, R. F., Bopp, G. R., and Bjorklund, W. R.: "Low Temperature Static Seals Using Elastomers and Plastics." Rev. Sci. Instr. 31, 1350-1351 (1960).

4. Dynamic Seals

Beard, C. S: "Control Valves For Cryogenic Fluids." Control Eng. Vol 13, No. 3, 67-72 (March 1966).

Charles, P., Prevost, C., and Testard, O.: Device For Connecting and Sealing-off Between Two Sections of a Pipeline For Conveying Liquefied Gas. U. S. Patent 3,344,803 (Oct 1967).

Decker, A. L.: "Unique Way to Seal Rotating Shaft." Chem. Eng. Vol 71, No. 15, 170-73 (July 1964).

Ferreira, L. E. and Briggs, D. D.: "Aluminum Oxide and Beryllium Oxide Ceramics--Seal Materials of the Future." SAE Aerospace Fluid Power Systems and Equip. Conf. Los Angeles (May 18, 1965).

Hetrick, J. K. and Linn, C. G.: Valve Lipseals. M-1 Sleeve-Type Thrust Chamber Valve. NASA-CR-54808 (March 1966).

Hudelson, J. C.: "Dynamic Instability of Undamped Bellows Face Seals In Cryogenic Liquid." Tech. Note No. D-3198 Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio (Jan 1966).

Jekat, W. K.: "Bearings, Seals, and Rotar Dynamics of Turbo-expanders and Similar High-speed Machinery." ASME Winter Annual Meeting. Chicago, Ill. (Nov 7-11, 1965).

Lavelle, J. E., Courtney, W. J., and Denholm, A. S.: High Vacuum Rotary Seal and Bearing Combination. (Ion Physics Corp., Burlington, Mass.) U. S. Patent 3,347,604 (Oct. 1967).

Roesche, E. and Pasternak, T.: Development of Large Size Bellows Face Type Seals For Liquid Oxygen and Oxygen/Hydrogen Hot Gas Service At Moderate to High Pressures. NASA-CR-54818 (Feb 1966).

Stearns, C. E.: "Cryogenic Face Seal." Mater. Design Eng. Vol 63, No. 4, 108-09 (April 1966).

MATERIALS GUIDE

COMPOSITIONS AND IDENTIFICATION OF MATERIALS

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A. ALUMINUM

Alloy Code	Designation	Composition* (Weight Percent)									
		Silicon	Iron	Copper	Manganese	Magnesium	Zinc	Titanium	Chromium	Others	Aluminum
A.1	1100	1.0 Si + Fe		0.20	0.05	--	0.10	--	--		99.00
A.2	2014	0.50 - 1.2	1.0	3.9 - 5.0	0.40 - 1.2	0.20 - 0.8	0.25	0.15	0.10		Balance
A.3	2020	0.40	0.40	4.0 - 5.0	0.30 - 0.8	0.03	0.25	0.10	--		
A.4	2024	0.50	0.50	3.8 - 4.9	0.30 - 0.9	1.2 - 1.8	0.25	--	0.10		
A.5	2219	0.20	0.30	5.8 - 6.8	0.20 - 0.40	0.02	0.10	0.02 - 0.10	--		
A.6	2618	0.25	0.9 - 1.3	1.9 - 2.7	--	1.3 - 1.8	--	0.04 - 0.10	--	0.9 - 1.2 Ni	
A.7	3003	0.6	0.7	0.20	1.0 - 1.5	--	0.10	--	--		
A.8	5052	0.45 Si + Fe		0.10	0.10	2.2 - 2.8	0.10	--	0.15 - 0.35		
A.9	5083	0.40	0.40	0.10	0.30 - 1.0	4.0 - 4.9	0.25	0.15	0.05 - 0.25		
A.10	5086	0.40	0.50	0.10	0.20 - 0.7	3.5 - 4.5	0.25	0.15	0.05 - 0.25		
A.11	5154	0.45 Si + Fe		0.10	0.10	3.1 - 3.9	0.20	0.20	0.15 - 0.35		
A.12	5456	0.40 Si + Fe		0.10	0.50 - 1.0	4.7 - 5.5	0.25	0.20	0.05 - 0.25		
A.13	6061	0.40 - 0.8	0.7	0.15 - 0.40	0.15	0.8 - 1.2	0.25	0.15	0.15 - 0.35		
A.14	7002	0.040	0.13	0.88	0.14	2.07	3.35	0.050	0.15		
A.15	7039	0.30	0.40	0.25	0.10 - 0.40	2.3 - 3.3	3.5 - 4.5	0.10	0.15 - 0.25		
A.16	7075	0.50	0.7	1.2 - 2.0	0.30	2.1 - 2.9	5.1 - 6.1	0.20	0.18 - 0.40		
A.17	7079	0.30	0.40	0.40 - 0.8	0.10 - 0.30	2.9 - 3.7	3.8 - 4.8	0.10	0.10 - 0.25		
A.18	X7106	0.35 Si + Fe		0.10	0.10 - 0.40	1.7 - 2.8	3.7 - 4.8	0.01 - 0.06	0.06 - 0.20	0.08 - 0.25 Zr	
A.19	7178	0.50	0.7	1.6 - 2.4	0.30	2.4 - 3.1	6.3 - 7.3	0.20	0.18 - 0.40		
A.20	355	5.0	--	1.3	--	0.5	--	--	--		
A.21	356	7.0	--	--	--	0.3	--	--	--		
A.22	Tens-50	7.6 - 8.6	0.20	0.10	0.10	0.40 - 0.55	0.10	0.1 - 0.2	--	0.15 - 0.30 Be	Balance

*Maximum unless shown as range.

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1. Alloy Designation System

A system of four-digit numerical designations for wrought aluminum and wrought aluminum alloys was adopted by The Aluminum Association in 1954 and became effective on October 1 of that year. The first digit of the designation serves to indicate alloy groups. The last two digits identify the aluminum alloy or indicate the aluminum purity. The second digit indicates modifications of the original alloy or impurity limits.

Designations for alloy groups are shown in the following tabulation.

		No.
Aluminum - 99.00% minimum and greater		1xxx
	Major Alloying Element	
Aluminum	Copper	2xxx
Alloys	Manganese	3xxx
Grouped	Silicon	4xxx
by Major	Magnesium	5xxx
Alloying	Magnesium and Silicon	6xxx
Elements	Zinc	7xxx
	Other Element	8xxx
Unused Series		9xxx

Aluminum and Aluminum Alloy Groups - In the four-digit system the first digit indicates the alloy group. The 1xxx series is for minimum aluminum purities of 99.00 percent and greater. The 2xxx through 8xxx series group aluminum alloys by major alloying elements.

Aluminum - In the 1xxx group for minimum aluminum purities of 99.00 percent and greater, the last two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when it is expressed to the nearest 0.01 percent. The second digit in the designation indicates modifications in impurity limits. If the second digit in the designation is zero, it indicates that there is no special control on individual impurities; integers 1 thru 9, which are assigned consecutively as needed, indicate special control of one or more individual impurities.

Aluminum Alloys - In the 2xxx through 8xxx alloy groups the last two of the four digits in the designation have no special significance but serve only to identify the different aluminum alloys in the group. When new alloys are developed to the point where they are used commercially, these last two digits are assigned consecutively beginning with xx01. The second digit in the alloy designation indicates alloy modifications. If the second digit in the designation is zero, it indicates the original alloy; integers 1 through 9, which are assigned consecutively, indicate alloy modifications.

Experimental Alloys - Experimental alloys are also designated in accordance with this system but they are indicated by the prefix X. The prefix is dropped when the alloy becomes standard. During development and before they are designated as experimental, new alloys are identified by serial numbers assigned by their originators. Use of the serial number is discontinued when the X number is assigned.

Temper Designations - The temper designation follows the alloy designation and is separated from it by a dash.

2. Temper Designation System

In effect since January 1, 1948, The Aluminum Association Temper Designation System is used for all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a dash.

Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

The basic temper designations and subdivisions are as follows:

-F As Fabricated: Applies to products which acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment. For wrought products, there are no mechanical property limits.

-O Annealed, Recrystallized (wrought products only): Applies to the softest temper of wrought products.

-H Strain-hardened (wrought products only): Applies to products which have their strength increased by strain-hardening with or without supplementary thermal treatments to produce partial softening.

The -H is always followed by two or more digits.

The first digit indicates the specific combination of basic operations, as follows:

-H1 Strain-hardened only: Applies to products that are strain-hardened to obtain the desired mechanical properties without supplementary thermal treatment.

The number following this designation indicates the degree of strain-hardening.

-H2 Strain-hardened and then partially annealed: Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the -H2 tempers have approximately the same ultimate strength as the corresponding -H3 tempers. For other alloys, the -H2 tempers have approximately the same ultimate strength as the corresponding -H1 tempers and slightly higher elongations.

The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

-H3 Strain-hardened and then stabilized: Applies to products which are strain-hardened and then stabilized by a low temperature heating to slightly lower their strength and increase ductility. This designation applies only to the magnesium-containing alloys which, unless stabilized, gradually age-soften at room temperature.

The number following this designation indicates the degree of strain-hardening remaining after the product has been strain-hardened a specific amount and then stabilized.

The second digit following the designations -H1, -H2, and -H3 indicates the final degree of strain-hardening. The hardest commercially practical temper is designated by the numeral 8 (full-hard). Tempers between -0 (annealed) and 8 (full hard) are designated by numerals 1 through 7. Material having an ultimate strength about midway between that of the -0 temper and that of the 8 temper is designated by the numeral 4 (half hard); between -0 and 4 by the numeral 2 (quarter hard); between 4 and 8 by the numeral 6 (three-quarter hard); etc. Numeral 9 designates extra hard tempers.

The third digit, when used, indicates that the degree of control of temper or the mechanical properties are different from, but within the range of, those for the two-digit -H temper designation to which it is added. Numerals 1 through 9 may be arbitrarily assigned and registered with The Aluminum Association for an alloy and product to indicate a specific degree of control of temper or specific mechanical property limits. Zero has been assigned to indicate degrees of control of temper or mechanical property limits negotiated between the manufacturer and purchaser which are not used widely enough to justify registration with The Aluminum Association.

The following three-digit -H temper designations have been assigned for wrought products in all alloys:

-H111 Applies to products which are strain-hardened less than the amount required for a controlled H11 temper.

-H112 Applies to products which acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment, but for which there are mechanical property limits or mechanical property testing is required.

-H311 Applies to products which are strain-hardened less than the amount required for a controlled H31 temper.

The following three-digit -H temper designations have been assigned for

Patterned or Embossed Sheet	Fabricated From
-H114	-O temper
-H134, -H234, -H334	-H12, -H22, -H32 temper, respectively
-H154, -H254, -H354	-H14, -H24, -H34 temper, respectively
-H174, -H274, -H374	-H16, -H26, -H36 temper, respectively
-H194, -H294, -H394	-H18, -H28, -H38 temper, respectively
-H195, -H395	-H19, -H39 temper, respectively

-W Solution Heat-Treated: An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated: for example, -W1/2 hour.

-T Thermally Treated to Produce Stable Tempers Other Than -F, -O, or -H: Applies to products which are thermally treated, with or without supplementary strain-hardening to produce stable tempers.

The -T is always followed by one or more digits. Numerals 2 through 10 have been assigned to indicate specific sequences of basic treatments, as follows:

-T2 Annealed (cast products only): Designates a type of annealing treatment used to improve ductility and increase dimensional stability of castings.

-T3 Solution heat-treated and then cold worked: Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

-T4 Solution heat-treated and naturally aged to a substantially stable condition: Applies to products which are not cold worked after solution heat-treatment, but in which the effect of cold work in flattening or straightening may be recognized in applicable specifications.

-T5 Artificially aged only: Applies to products which are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, to improve mechanical properties and/or dimensional stability.

-T6 Solution heat-treated and then artificially aged: Applies to products which are not cold worked after solution heat treatment, but in which the effect of cold work in flattening or straightening may be recognized in applicable specifications.

-T7 Solution heat-treated and then stabilized: Applies to products which are stabilized to carry them beyond the point of maximum hardness, providing control of growth and/or residual stress.

-T8 Solution heat-treated, cold worked, and then artificially aged: Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

-T9 Solution heat-treated, artificially aged, and then cold worked: Applies to products which are cold worked to improve strength.

-T10 Artificially aged and then cold worked: Applies to products which are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, and then cold worked to improve strength.

A period of natural aging at room temperature may occur between or after the operations listed for tempers -T3 through -T10. Control of this period is exercised when it is metallurgically important.

Additional digits may be added to designations -T2 through -T10 to indicate a variation in treatment which significantly alters the characteristics of the product. These may be arbitrarily assigned and registered with The Aluminum Association for an alloy and product to indicate a specific treatment or specific mechanical property limits.

The following additional digits have been assigned for wrought products in all alloys:

-TX51 Stress-relieved by stretching: Applies to products which are stress-relieved by stretching the following amounts after solution heat-treatment:

Plate	1 1/2 to 3% permanent set
Rod, Bar and Shapes	1 to 3% permanent set

Applies directly to plate and rolled or cold-finished rod and bar. These products receive no further straightening after stretching.

Applies to extruded rod, bar and shapes when designated as follows:

-TX510 Applies to extruded rod, bar and shapes which receive no further straightening after stretching.

-TX511 Applies to extruded rod, bar and shapes which receive minor straightening after stretching to comply with standard tolerances.

-TX52 Stress-relieved by compressing: Applies to products which are stress-relieved by compressing after solution heat-treatment.

-TX53 Stress-relieved by thermal treatment

The following two-digit -T temper designations have been assigned for wrought products in all alloys:

-T42 Applies to products solution heat-treated by the user which attain mechanical properties different from those of the -T4 temper.*

-T62 Applies to products solution heat-treated and artificially aged by the user which attain mechanical properties different from those of the -T6 temper.*

*Exceptions not conforming to these definitions are 4032-T62, 6101-T62, 6061-T62, 6062-T62, 6063-T42 and 6463-T42.

B. STAINLESS STEEL

Alloy Code	Designation	Composition* (Weight Percent) Carbon	Manganese	Phosphorus	Sulfur	Silicon	Chromium	Nickel	Others	Iron	Type of Structure
B.1	301	0.08 - 0.20	2.00	0.04	0.03	1.00	16.0 - 18.0	6.0 - 8.0		Balance	Nonhardenable, austenitic
B.2	302	0.08 - 0.20	2.00	0.04	0.03	1.00	17.0 - 19.0	8.0 - 10.0			
B.3	303	0.015	2.00			1.00	17.0 - 19.0	8.0 - 10.0	P, S, Se = 0.07 min		
									Zr, Mo = 0.60		
B.4	304	0.08	2.00	0.04	0.03	1.00	18.0 - 20.0	8.0 - 11.0			
	304L	0.03	2.00	0.04	0.03	1.00	18.0 - 20.0	8.0 - 11.0			
B.5	310	0.25	2.00	0.04	0.03	1.50	24.0 - 26.0	19.0 - 22.0			
B.6	321	0.08	2.00	0.04	0.03	1.00	17.0 - 19.0	8.0 - 11.0	Ti = 6 x C - 0.7		
B.7	347	0.08	2.00	0.04	0.03	1.00	17.0 - 19.0	9.0 - 12.0	Cb or Ta = 10 x C - 1.1		Nonhardenable, austenitic
B.8	410	0.15	1.00	0.04	0.03	1.00	11.5 - 13.5	0.50	Zr, Mo = 0.60		Hardenable, martensitic
									Cu = 0.50		
B.9	416	0.15	1.25			1.00	12.0 - 14.0				
B.10	440C	0.95 - 1.20	1.00	0.04	0.03	1.00	16.0 - 18.0	0.75	Mo = 0.40 - 0.60		Hardenable, Martensitic
B.11	A-286	0.08	2.00	0.04	0.03	1.00	13.5 - 16.0	24.0 - 27.0	Mo = 1.0 - 1.5;		Precipitation hardenable, austenitic
									Ti = 1.9 - 2.3;		
									Al = 0.35		
B.12	17-4PH	0.07	1.00	0.04	0.03	1.00	15.5 - 17.5	3.0 - 5.0	Cu = 3.0 - 5.0		Precipitation hardenable, martensitic
									Cb + Ta = 0.15 - 0.45		
B.13	17-7PH	0.09	1.00	0.04	0.03	1.00	16.0 - 18.0	6.7 - 7.75	Al = 0.75 - 1.50		Precipitation hardenable, semi-austenitic
B.14	AM-350	0.07 - 0.12	0.50 - 1.25	0.04	0.03	0.50	16.0 - 17.0	4.0 - 5.0	Mo = 2.5 - 3.25		
									N = 0.07 - 0.13		
B.15	AM-355	0.10 - 0.15	0.50 - 1.25	0.04	0.03	0.50	15.0 - 16.0	4.0 - 5.0	Mo = 2.5 - 3.25	Balance	Precipitation hardenable, semi-austenitic
									N = 0.07 - 0.13		

*Maximum unless shown as range.

The stainless steels can be categorized into one of four general classifications, as shown in the following tabulation.

Group	Major Alloy Content	Hardenable by Heat Treatment	Method	Structure	Example
1	Chromium	Yes	Quench and Temper	Martensitic	410
2	Chromium	No	--	Ferritic	430
3	Chromium-nickel	No	--	Austenitic	304
4	Chromium-nickel	Yes	Precipitation Hardening	Austenitic Semi-austenitic Martensitic	A-286 17-7PH 17-4PH

Steels in the first group contain chromium and carbon in such proportions that hardening will occur due to thermal transformation. These steels are hardened by the normal practices used to treat alloy steels. Chromium content for these steels usually is in the range 11.5 to 18.0 percent; carbon is usually between 0.10 and 1.20 percent. These alloys are subject to the ductile-to-brittle transition behavior common to body-centered cubic metals, and therefore, are not satisfactory for cryogenic service.

The second group of steels is characterized by a ratio of chromium/carbon so that transformation effects are reduced. Therefore, these steels cannot be hardened by thermal treatment. Cold working may be used to achieve strengthening. The ferritic structure (body-centered cubic) is also subject to transition behavior at low temperatures, and as a result, these steels are also unsuitable for low temperature service.

Stainless steels of the third group are characterized by sufficient alloy content to stabilize the austenite (face-centered cubic) phase. They cannot be hardened by heat treatment. However, cold working can be used to obtain strengthening. The response to such working varies with each type; however, in general, response decreases with increasing alloy content. Standard tempers have been established for cold rolled stainless steel. The minimum mechanical property requirements for these tempers are given below in the following tabulation.

Temper	Tensile Strength 10^3 psi	Yield Strength 0.2% Offset 10^3 psi	Elongation (% in 2 in.)	Hardness (R_c)
1/4 Hard	125	75	25	25
1/2 Hard	150	110	15 or 18	32
3/4 Hard	175	135	10 or 12	37
Full Hard	185	140	8 or 9	41
Extra Full Hard	200	--	--	45

The 301 and 304L have sufficiently low alloy and/or carbon content so that they work harden rapidly. This is partially a result of transformation in these metastable compositions to the body-centered phase. This becomes a particular problem at cryogenic temperatures, where heavy cold working causes a large amount of transformation to occur upon cooling. However, by selection of higher alloy grades or the metastable grades with smaller amounts of cold work, the problem can be avoided. The toughness of austenitic stainless steels is extremely high. These steels together with the aluminum alloys have been the principal structural materials for cryogenic service.

The precipitation hardening stainless steels were developed to meet the requirements of fabricability and higher strength dictated by our defense program. The austenitic grade (i.e., A-286) contains sufficient alloy content to remain austenitic on cooling to room temperature. Moderate supersaturation of the austenite occurs during cooling as a result of a reduction in solubility of certain solute elements with decreasing temperature. Precipitation can be achieved at about 1300°F to develop matrix strengthening. Semi-austenitic alloys (17-7PH, AM-350) remain austenitic after cooling from the annealing temperature (~ 1950°F). Subsequent heating at intermediate temperatures depletes the austenite of carbon and chromium sufficiently to permit martensite to form on cooling or cold rolling. The transformation product is then aged to develop full strength properties. Martensitic precipitation hardenable stainless steels transform from austenite to martensite on cooling to room temperature. The transformed product is only partially hardened. Aging at temperatures in the vicinity of 900°F causes second phase precipitation and further strengthening.

C. TITANIUM

Alloy Code	Designation	Composition* (Weight Percent)										Type of Structure
		Carbon	Oxygen	Hydrogen	Nitrogen	Aluminum	Vanadium	Zirconium	Tin	Iron	Others	Titanium	
C.1	Commercial Purity	0.08		0.015 (Sheet)	0.05					0.25		Balance	Alpha
C.2	Ti - 5Al - 2.5Sn	0.08	0.20	0.0175 (Sheet)	0.05	4.0 - 6.0			2.0 - 3.0	0.50			
	Ti - 5Al - 2.5Sn (ELI)	0.05	0.12	0.0175 (Sheet)	0.05	4.7 - 5.6			2.0 - 3.0	0.25			
C.3	Ti - 8Al - 1Mo - 1V	0.08	0.10	0.015 (Sheet, Plate)	0.05	7.5 - 8.5	0.75 - 1.25			0.25	Mo = 0.75 - 1.25		
C.4	Ti - 8Al - 2Cb - 1Ta	0.05	0.10	0.015 (Sheet)	0.05	7.5 - 8.5				0.25	Cb = 1.75 - 2.25		
											Ta = 0.75 - 1.25		
C.5	Ti - 7Al - 12Zr	0.04	0.10	0.010	0.03	6.7 - 7.5		11.5 - 12.5		0.15			Alpha
C.6	Ti - 3Al - 2.5V	0.05		0.015	0.015	2.5 - 3.5	2.0 - 3.0			0.30	0.20		Alpha - Beta
C.7	Ti - 6Al - 4V	0.08	0.20	0.015 (Sheet)	0.05	5.75 - 6.75	3.5 - 4.5			0.25			Alpha Beta
	Ti - 6Al - 4V (ELI)	0.08	0.13	0.015 (Sheet)	0.05	5.75 - 6.75	3.5 - 4.5			0.25			Alpha - Beta
C.8	Ti - 13V - 11Cr - 3Al	0.05	0.20	0.025 (Sheet)	0.08	2.5 - 3.5	12.5 - 14.5				Cr = 10.0 - 11.0	Balance	Beta

*Maximum unless shown as range.

Titanium and its alloys fall into three general types:

1) Alpha;

2) Alpha-beta;

3) Beta.

Commercially pure titanium, and alloys such as Ti-5Al-2.5Sn or Ti-8Al-1Mo-1V are in the alpha category. They are categorized by a hexagonal close-packed lattice structure. Alpha alloys exhibit generally good low temperature ductility for hexagonal close-packed metals. An outstanding material for service down to -423°F is Ti-5Al-2.5Sn prepared with low-oxygen content (ELI grade; extra low interstitial). Commercial-purity grades containing high oxygen contents and high aluminum alloys, such as Ti-8Al-1Mo-1V and Ti-8Al-2Cb-1Ta, generally show a loss of toughness at very low temperatures. Alpha alloys cannot be strengthened by heat treatment and are generally utilized in the annealed condition.

Alpha-beta alloys contain a mixture of the hexagonal alpha phase and the body-centered cubic beta phase. These alloys show considerable variation in cryogenic properties as a result of composition. An alloy containing a high percentage of beta (~50 percent), such as Ti-8Mn, is extremely brittle at -423°F. Alloys lean in beta content, such as Ti-6Al-4V, exhibit rather satisfactory low temperature properties. Lean beta alloys are amenable to heat treatment. However, for cryogenic service, some loss of toughness naturally results from strengthening by thermal treating.

Beta alloys are single phased and crystallize in the body-centered cubic lattice. The only commercial beta alloy is the Ti-13V-11Cr-3Al. This alloy, because of its crystal structure and resulting ductile-brittle transition behavior is unsatisfactory for low temperature service.

The presence of the interstitial elements (carbon, oxygen, nitrogen, and hydrogen) strengthen titanium alloys at room temperature without serious impairment of ductility and toughness. However, at cryogenic temperatures the interstitials can be very detrimental to mechanical properties. Although nitrogen appears to be the most deliterous interstitial element, it is generally present in sufficiently small amounts so that it is not troublesome. However, oxygen, which is somewhat less potent as a strengthener than nitrogen, appears in sufficiently large amounts to be a problem.

For cryogenic applications, the two most promising candidates, Ti-5Al-2.5Sn and Ti-6Al-4V, have been made available with controlled oxygen content and identified as extra-low interstitial grade. The maximum permissible oxygen content for the Ti-5Al-2.5Sn alloy is 0.12 weight percent whereas the Ti-6Al-4V composition specifies a maximum of 0.13 weight percent.

The presence of iron, a beta stabilizing element, has been shown to result in a loss of toughness at cryogenic temperatures. As a result, for the Ti-5Al-2.5Sn ELI composition, the additional limitation of iron to a maximum of 0.25 weight percent has been imposed.

D. SUPERALLOYS

Alloy Code	Designation	Composition (Weight Percent)											
		[illegible]	Manganese	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Nickel-[illegible]				[illegible]								
D.1	Nickel-"[illegible]"	0.15	0.35	0.35	99.0 min					0.40			[illegible]
D.2	Inconel	0.15	1.00	0.05	Ni + Co = [illegible].0 min		4.0 - 1[illegible].0			[illegible]			
D.3	Inconel X (Inconel X-750)	0.08	1.00	0.30	Balance	1.00	4.0 - [illegible]			[illegible]	[illegible] - 2.75	0.40 - 1.00	[illegible] - 1.2
D.4	K-Monel	0.25			63.0 - 70.0					[illegible]	[illegible] - 1.00	[illegible]	[illegible] Balance
D.5	S-Monel	0.25	1.50	3.5 - 4.5	60.0 min					[illegible]		[illegible]	[illegible] - 31.0
D.6	Hastelloy B	0.05	1.00	1.00	Balance	2.50	[illegible].00	[illegible] - 30.0		4.0 - [illegible]			
D.7	Hastelloy C	0.08	1.00	1.00	Balance	2.50	4.5 - 16.5	15.0 - 17.0	3.0 - [illegible]	4.5 - 7.0			
D.8	Hastelloy X	0.05 - 0.15	1.00	1.00	Balance	[illegible].50 - 2.50	[illegible]	[illegible] - 10.0	[illegible] - 1.00	17.0 - 20.0			
D.9	René 41	0.12	0.10	0.50	Balance	10.0 - 12.0	[illegible] - 20.0	[illegible]		[illegible]	3.0 - 3.3	1.4 - 1.6	
D.10	R-235	0.1[illegible]	0.2[illegible]	0.60	Balance	[illegible]	[illegible] - 17.0	[illegible] - 6.5		[illegible] - 11.0	[illegible]	[illegible] - 2.25	
D.11	D-979	0.08	0.75	0.75	42.0 - 49.0		4.0 - 16.[illegible]	3.0 - 4.5	3.0 - 4.5	Balance	[illegible] - 3.3	[illegible] - 1.3	
D.12	L-605 (HS 25)	0.05 - 0.15	1.00 - 2.00	1.00	9.0 - 11.0	Balance	19.0 - 21.0		14.0 - 16.0	3.00			
D.13	Inconel 718	0.10	0.35	0.35	Ni + Co = 50.0 - [illegible]	1.00	[illegible] - 21.0	[illegible] - 3.30		Balance	[illegible] - 1.15	[illegible] - 0.8	[illegible]

Maximum unless shown as range or minimum.

E. ALLOY STEELS

Alloy Code	Designation	Composition (Weight Percent)										
		[illegible]	Manganese	Phosphorus	Sulfur	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Other	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]							[illegible]
E.2	4340	0.38 - [illegible]	0.65 - 0.85	0.040	0.040	[illegible].20 - 0.3[illegible]	0.[illegible] - 0.90	1.65 - 2.00		[illegible] - 0.30		
E.3	H-11 (5% Cr)	0.3[illegible] - [illegible]	[illegible] - 0.40	0.020	[illegible].020	[illegible] - 1.00	[illegible] - 5.25		0.40 - 0.60	[illegible]		
E.4	2800 (9% Ni)	0.13	[illegible]	0.03[illegible]	[illegible].040	[illegible] - 0.30		[illegible].5 - 9.[illegible]				
E.5	18% Ni Maraging											
	Grade 200	[illegible]	0.10	0.01	0.01	0.10		1[illegible].0 - 19.0		[illegible] - 4.5	Co = 7.0 - [illegible].5 Ti = 0.15 - 0.30 Al = 0.05 - 0.15	
	Grade 250	0.03	0.10	0.01	[illegible].01	[illegible].10		17.0 - [illegible]		[illegible] - [illegible].3	Co = [illegible].0 - [illegible] Ti = 0.30 - [illegible].50 Al = 0.05 - 0.15	
	Grade 300	0.03	0.10	0.01	0.01	0.10		[illegible]		[illegible] - 5.1	Co = [illegible] Ti = 0.30 - [illegible] Al = 0.05 - 0.15	Balance

Maximum unless shown as range or minimum.

F. MISCELLANEOUS METALS AND ALLOYS

Alloy Code	Designation	Composition* (Weight Percent)
F.1	Copper-OFHC	Cu = 99.95 min
F.2	Beryllium Copper	Be = 1.80 - 2.05, Ni + Co = 0.20 min, Ni + Co + Fe = 0.60, Cu + other reported elements = 99.5 min
F.3	70/30 Brass	Cu = 68.5 - 71.5, Pb = 0.07, Fe = 0.05, Zn = balance
F.4	Elgiloy	Typical: C = 0.15, Mn = 2, Co = 40, Cr = 20, Ni = 15 Fe = 15, Mo = 7, Be = 0.05
F.5	Invar	C = 0.18, Mn = 0.42, Ni = 35.5, Fe = balance
F.6	Ni Span C	C = 0.6, Mn = 0.8, Si = 1.00, Cr = 4.9 - 5.75, Ni + Co = 41.0 - 43.5 Co = 1.0, Ti = 2.2 - 2.75, Al = 0.3 - 0.8, Cr + (Ti - 4 x C) = 7.7 - 8.1, Fe = balance

*Maximum unless shown as range, minimum or typical.

SOURCES OF CRYOGENIC MATERIALS PROPERTY DATA

This Handbook covers many of the metallic and non-metallic materials that are being considered for use in cryogenic service. The Handbook emphasizes the mechanical properties, but also includes some physical properties of these materials in the range from -459°F to room temperature. Recognizing that it is impractical, if not impossible, to include all pertinent data in one document, this subsection identifies alternative sources for cryogenic data. These include both reference documents and data centers. All of the data centers cited are either government operations or wholely or partially funded by the federal government. Seven such selected sources are briefly described in this subsection.

CRYOGENIC DATA CENTER
National Bureau of Standards,
Institute for Materials Research
Boulder, Colorado. 80302

1. Data Compilation Activities

The Cryogenic Data Compilation Unit is engaged in the critical evaluation and compilation of data on the properties (thermodynamic, transport, and other thermophysical properties) for the principal fluids (and common mixtures of these fluids) used at low temperatures, namely:

Helium	Nitrogen	Carbon Monoxide	Methane
Hydrogen	Oxygen	Fluorine	Xenon
Neon	Air	Argon	Krypton

The scope of the compilation program also includes the properties of metallic elements, selected alloys, and element dielectrics as follows:

Electrical Resistivity	Thermal Conductivity	Specific Heat
Dielectric Constant	Thermal Expansion	Enthalpy

Ultimately it is expected that data will be compiled for the mechanical properties of structural materials; however, it may be some time yet before tasks are started.

The thermodynamic properties of fluids being pursued are:

Pressure-Volume-Temperature
Vapor Pressure, Latent Heat, Saturation Densities
Isothermal Compressibility, Volume Expansivity
Entropy, Enthalpy, Internal Energy
Specific Heats (C_p, C_v, C_{sat})
Velocity of Sound

The transport properties of fluids included in the program are:

Thermal Conductivity	Prandtl Number	Thermal Diffusion Coefficients
Viscosity	Diffusion Coefficients	

Other thermophysical properties include:

Dielectric Constant	Electrical Resistivity	Magnetic Properties
Refractive Index	Surface Tension	Optical Properties
Dielectric Breakdown		

The literature is monitored on a continuing basis for all phases of the above program. As specific tasks are undertaken, comprehensive bibliographies are prepared and sometimes published. Task notebooks are made for preliminary selection of data and, where feasible, preliminary data sheets are issued. Critical evaluation is done by the senior staff consisting of two physicists, one engineer (thermodynamic), chemist, and physical chemist. The staff collaborates with theoretical groups within NBS and with consultants for better development of the theory where pertinent. The Data Compilation Unit operates as part of the National Standard Reference Data Program. The work is currently sponsored by the National Aeronautics and Space Administration.

2. Documentation Activities

Literature Searching - An awareness of publications and reports of cryogenic interest is maintained by the regular review of nearly two hundred periodicals cover to cover, by a weekly review of the "Current Contents" service, by reviewing some 15 abstract journals, and by noting references in cryogenic documents. Some 150 to 200 items are noted weekly.

Literature Procurement - Published literature is obtained from local, national, and foreign libraries. Report literature is procurred mostly from the large national centers (NASA, DDC, and the Clearinghouse). Many new reports are obtained directly from the corporate source as a part of the Data Center's program of information exchange.

Cataloging, Coding, and Machine Processing - In addition to standard library cataloging of pertinent literature selected for the system, it is coded into nine main subject categories such as properties of solids and fluids, cryogenic processes and equipment, instrumentation and laboratory apparatus, cryogenic techniques, etc. Further characteristic coding is then assigned as to the type of document, temperature range, and type and range of the data, etc. This is followed by comprehensive subject coding based on the Data Center's thesaurus or dictionary of terms.

Bibliographic Storage and Retrieval - All cataloging and coding is converted to machine readable form for automated processing on the Boulder Laboratories' Control Data Corporation 3600 computer. The principal programs used are for searching, dictionary term identification, and for catalog tape output. Smaller programs are also in use for additional indexing, tape updating, corrections, etc. Custom bibliographies are prepared for specific subjects or for broad subject areas. Indexing follows from the nature of search queries and can be quite detailed. An average of two major searches are made each week plus a number of small ones for answers to single questions.

Distribution of Literature and Data - Announcements and abstract cards of new literature evolving from the Cryogenic Laboratory's Research Program are sent to more than 4000 persons and institutions periodically. Nearly 500 separate items of literature are now available. Fifteen to twenty thousand documents are distributed each year in response to some 2000 orders. This distribution is now handled by the Clearinghouse for Federal Scientific and Technical Information (CFSTI), Springfield, Virginia. 22151.

3. Cryogenic Data Center Services

Literature Searches - Nearly 50,000 accessions of cryogenic literature have been entered into the Data Center's system. Approximately 25,000 of these on properties of materials (for both fluids and solids) have been processed for machine searching. Detailed and/or extensive bibliographies can be prepared with computer facilities. Likewise, some 3000 patents, 4000 articles on processes and equipment, and 1000 articles on instrumentation have now been processed for machine retrieval. The cost of custom searches is based on a rate of $12* per minute of computer time plus 15¢* per reference for listing and indexing. Simple searches can be made for as little as $25 to $30.* More extensive searches are proportionately higher. The feasibility and estimated cost of a search can be obtained from Mr. Neil A. Olien, Project Leader for the Documentation Group. His telephone number is 447-1000, Ext. 3834, Area Code 303.

Current Awareness Service - Weekly lists of new literature of cryogenic interest are prepared and distributed to subscribers. The subscription price is $10* per year ($15* for foreign air mail delivery), for 52 issues. A subscription may be obtained by ordering from the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado 80302.

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*The prices listed were in effect on the date of the issue of Supplement 4 of this Handbook (8-68) but are subject to change.

Superconducting Devices - In cooperation with staff of the Stanford Research Institute and the Office of Naval Research, the Cryogenic Data Center compiles a quarterly bibliography of references of superconducting devices and theory and experiment related to devices. Subscriptions are $15* per annum for four issues. The single issue price is $5.* Subscriptions may be ordered as for the Current Awareness Service.

Preliminary Data and Advice - This service on the thermodynamic and transport properties of cryogenic fluids a d selected solids can be obtained from Mr. Hans Roder, Project Leader for the Data Compilation Group. His telephone number is 447-1000, Ext. 3528, Area Code 303.

Announcements of Cryogenic Laboratory Publications and Reports - These items are available to anyone wishing to be placed on the mailing list by writing Attn: Mrs. Jo R. Mendenhall, Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado 80302. Distribution of this literature is being handled by the government Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151. Ordering information is included with the announcements.

*The prices listed were in effect on the date of issue of Supplement 4 of this Handbook (8-66) but are subject to change.

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

DMIC is an information analysis center sponsored by the Department of Defense and operated under an Air Force contract. Its purpose is to collect, analyze, interpret, and disseminate technical information and data about special metals important to the defense system.

DMIC and its predecessor, the Titanium Metallurgical Laboratory have operated at Battelle Memorial Institute, Columbus Laboratories, since 1955. Its current scope includes: aluminum, titanium, magnesium, beryllium, refractory metals, high-strength steels (including stainless and maraging steels), and superalloys.

Regular publications of DMIC include formal reports, technical memoranda, technical notes, reviews of recent developments, and data sheets. DMIC also responds to technical inquiries, which are handled by members of the Battelle staff of professional scientists and engineers, as needed. A quick-response storage-and-retrieval system supplies the user (Battelle/DMIC staff member or qualified visitor) with the latest information and data in a form most suitable to his needs.

DMIC services are availabl without charge to U. S. Government Agencies, their contractors, subcontractors, suppliers, and others in a position to assist the defense effort.

Addresses:

Defense Metals Information Center
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201
Director, R. J. Runck
(614) 299-3151

Defense Metals Information Center
Battelle Memorial Institute
925 Harbor Plaza
Long Beach, California 90802
E. W. Cawthorne, West Coast Representative
(213) 436-1241

MECHANICAL PROPERTIES DATA CENTER
Traverse City, Michigan 49684

The Mechanical Properties Data Center (MPDC) has been an operating Air Force Materials Information Center for eight years, and is also an officially designated DOD Information Analysis Center. MPDC's purpose is acquisition, evaluation, organization, and dissemination of mechanical properties data of structural materials. Major emphasis is on metal alloys.

MPDC's data collection includes published and unpublished reports from the U. S. Department of Defense, NASA, industry, research centers, and universities. Data, related variables, and supporting information are extracted from incoming reports by the Center's technical staff and stored, first in punched cards, then in magnetic tape. Each month between 8,000 and 10,000 test records are added to data in the system, which now represents well over 4,000 specific alloys, and about three quarters of a million individual mechanical properties tests.

MPDC's services are available to government agencies, the entire aerospace community, and industry. Data provided by the Center are used for engineering, design, quality control, analytical programs, and in other areas where comprehensive detailed data displays are required.

One of the primary functions of MPDC's system is to make detailed data available as needed for specific applications. To accomplish this efficiently, users requesting data are provided with graphic or tabular displays that meet their individual requirements as nearly as possible. In addition to test results for each specimen, the displays include all pertinent variables and supporting bibliographic information. Because of the amount of data stored in the system, users are urged to state their requirements as exactly as possible. This helps avoid both unnecessary expense and displays, including unwanted data.

In 1966, because of increasing search volume, it became necessary to charge all users, except government agencies. The Air Force supports the entire cost of data input, and system maintenance and expansion. Data Center fees, with the user in mind are kept as low as possible, and are only intended to defray a portion

of actual search costs. MPDC's fee for a search cannot exceed a maximum of $75.00* no matter how large the data display, and the average search costs the user less than $50.00.* The basic search and retrieval charge is $25.00.* In addition, graphic and tabular displays resulting from a data file search are billed at the rate of $0.25* per test specimen, with a maximum total price per search of $75.00.*

A search is normally defined as the data and information available on each alloy/test type combination specified in an inquiry. For example, a request for information on the effect of elevated temperature on the tensile properties (ultimate, yield, elongation, modulus, Poisson's ratio, etc) of INCO 901, and Udimet 200, would be processed and billed as two searches. Tensile and creep properties of the two alloys would produce four searches. Searches always include complete bibliographic information.

Organizations originating published or unpublished mechanical properties test data for any purpose, are asked to seriously consider including the data in MPDC's files. The Data Center honors any proprietary distribution limitations imposed by data sources. Searches always include complete bibliographic information, thus providing sources of data with credit.

Other specialized services, including consultation and data analyses for specific applications, can be provided by MPDC. Contact MPDC by mail, phone or TWX, if you have questions about the Center's services.

*The prices listed were in effect on the date of issue of Supplement 4 to this Handbook (8-68) but are subject to change.

THERMOPHYSICAL PROPERTIES RESEARCH CENTER
Purdue University Research Park
2595 Yeager Road
West Lafayette, Indiana 47906

1. Areas of Interest

The areas of interest are thermophysical properties of matter, including the following properties: thermal conductivity, accommodation coefficient, thermal contact resistance, thermal diffusivity, specific heat, viscosity, emissivity, reflectivity, absorptivity, transmissivity, solar radiation coefficient, Prandtl Number, diffusion coefficient, thermal linear expansion coefficient, thermal volumetric expansion, coefficient, and surface tension. Thermophysical properties are keyed to all matter; representative groupings are: slags, scales, ceramics, oxides, glasses, mixtures, solutions, metals, nonmetals, minerals, compounds, coatings cermets, pharmaceuticals, cosmetics, toiletries, petroleum products, animal and vegetable substances, fabrics, yarns, rubbers, plastics, resins, polymers, paper and wood products, and building materials.

2. Holdings

The Center has 45,000 unclassified technical papers, of which more than 80 percent are on microfiche, with an annual accession rate of about 8,000.

3. Publications

Thermophysical Properties Research Literature Retrieval Guide (three-book set providing 33,700 references keyed to properties for 45,000 different materials); Thermophysical Properties of High Temperature Solid Materials [6-volume (9 books) reference work with 8,500 pages]; TPRC Series on Thermophysical Properties of Matter, 13 volumes (First 7 volumes in press); Masters Theses in the Pure and Applied Sciences (annual).

4. Information Services

The Center answers inquiries, makes referrals, provides reference services, makes literature searches through computer-assisted retrieval system, reproduces research documents on microfiche, and provides consulting and advisory services to Government agencies and industry. Except for special arrangements witn selected agencies, nominal fees are requested for services rendered.

The Center has a modern, well-equipped laboratory for varied research programs; equipment to provide accurate temperature measurements, calorimetry, and radiometry; an instrument machine shop, data reduction plotter, and the use of Purdue University Computer Center facilities (IBM 7094 and CDC 6500).

For details on services and publications, write or call

Mr. Wade H. Shafer
Thermophysical Properties Research Center
Purdue University
2595 Yeager Road
West Lafayette, Indiana 47906
(317) 743-3827

A COMPENDIUM OF THE PROPERTIES OF
MATERIALS AT LOW TEMPERATURES
WADD TR-60-56, Parts I, II, and III,
October 1960

The compendium is a three-part publication prepared by the National Bureau of Standards, Cryogenic Engineering Laboratory under Air Force sponsorship. Although somewhat dated, these documents contain much valuable information and because of wide distribution are available in many libraries.

Part I covers the following properties and fluids:

Fluid	Property
Helium	Density
Hydrogen	Expansivity
Neon	Thermal conductivity
Nitrogen	Specific heat and enthalpy
Oxygen	Transition heat
Air	Phase equilibria
Carbon Monoxide	Dilectric constant
Fluorine	Absorption
Argon	Surface tension
Methane	Viscosity

Part II deals with solid materials, grouped according to the following categories and properties:

Category	Property
Pure metals	Thermal expansion
Nonferrous	Thermal conductivity
Ferrous alloys	Specific heat and enthalphy
Inorganic Compounds	
Organic Compounds	

Part III is a cross indexed bibliography of pertinent references.

LOW TEMPERATURE MECHANICAL PROPERTIES
OF COPPER AND SELECTED COPPER ALLOYS -
NATIONAL BUREAU OF STANDARDS MONOGRAPH 101 -
A Compilation from the Literature

This extremely complete reference was prepared by the Institute for Materials Research, National Bureau of Standards, Boulder, Colorado, under the sponsorship of the International Copper Research Association and the Copper Development Association. It was issued in December 1967. The materials covered in NBS Monograph 101 include: pure copper; some of the copper-zinc, copper-nickel, and copper-aluminum solid solution alloys; and some of the copper-silicon, aluminum bronze, and copper-zirconium age-hardening alloys.

The compilation is divided into four sections. Section I is intended for quick reference for those who are interested in average values. Section II includes data from most of the investigators who have published results on the mechanical properties of copper and its alloys. Section III consists of tables classifying the investigations that were not included in Section II. These usually involve studies in which data were obtained at only one temperature. Section IV is a listing in alphabetical order, of all the references used.

Copies of NBS Monograph 101 may be obtained from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402. The Price is $2.75.

AEROSPACE STRUCTURAL METALS HANDBOOK

This handbook was first titled the "Air Weapons Materials Application Handbook, Metals and Alloys." The first edition was prepared by the Syracuse University Research Institute, Syracuse, New York, and was completed in December 1959. It contained information on 93 metals and alloys. Information on 39 additional metals and alloys was added in Supplement I to the first edition, completed in August 1962.

The present version of the handbook, titled the "Aerospace Structural Metals Handbook," was completed in March 1963. Revision supplements to the "Aerospace Structural Metals Handbook" were issued in 1964, 1965, 1966, and 1967. In its present form the handbook consists of three volumes:

Volume I - Ferrous Alloys;

Volume II - Non-Ferrous, Light Metal Alloys;

Volume III - Non-Ferrous, Heat Resistant Alloys.

The Syracuse University Research Institute was responsibl for the handbook until the fourth supplement was issued in 1967. Responsibility was then transferred to the Mechanical Properties Data Center.

An important part of MPDC's role in making materials information available is the preparation of new chapters and revisions for the handbook. Both new chapters, and revisions incorporating important additional current information, are prepared on a continuing basis by the Data Center's technical staff. The handbook, and its' supplements presently cover 178 alloys, providing typical data and information on each alloy, rather than minimum design values. Handbook alloy chapters include:

General description of the metal;

Specifications and composition,

Heat treatment and hardness;

Available forms and conditions;

Melting and casting practices;

Physical and chemical properties;

Mechanical properties at room and elevated temperatures, such as tensile strength, fatigue, creep, and impact propties;

Fabrication detail on items such as formability, machinability, weldability, and heat treatment.

An arrangement has been made with Materials Engineering, for distribution of individual or multiple copies of new handbook chapters.

Alloys covered by new or revised handbook chapters are carefully selected from a large list of candidate alloys. New chapter coverage includes several steels, titanium, nickel-base, aluminum, magnesium, and cobalt-base alloys. Packages including completed and in-process chapters may be purchased at a special subscription rate, and will be forwarded as finished.

Interested individuals should address requests for details to:

Reader Service Department
Materials Engineering
430 Park Avenue
New York, New York 10022

Al
4.5 Cu
1 Mn
1 Si
0.5 Mg

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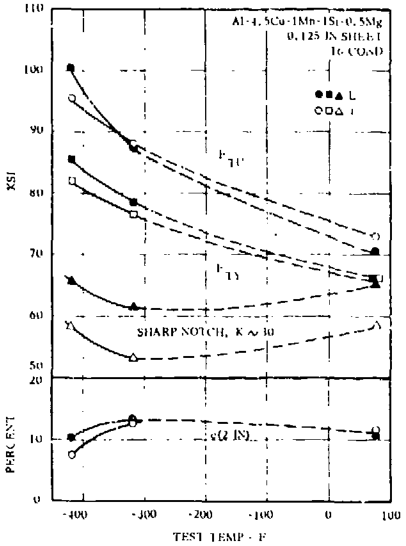

FIG. 3.03712 EFFECT OF LOW TEMPERATURES ON TENSILE AND SHARP NOTCH PROPERTIES OF SHEET IN T6 CONDITION (12)

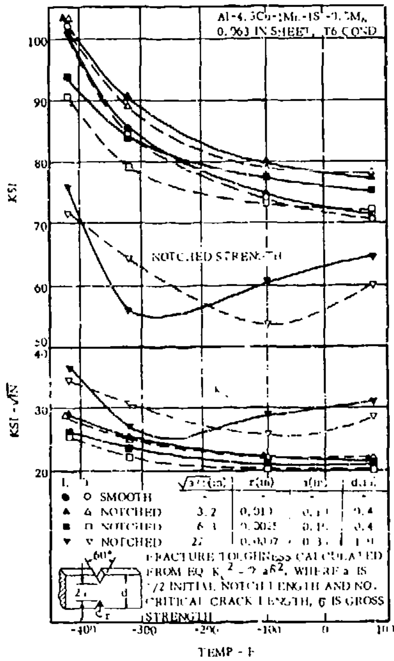

FIG. 3.03713 EFFECT OF LOW TEST TEMPERATURES ON NOTCH STRENGTH AND FRACTURE TOUGHNESS OF SHEET IN T6 CONDITION (21, p.193-195)

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TYPICAL PAGE FROM AEROSPACE
STRUCTURAL METALS HANDBOOK

TESTING METHODS

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This section on testing methods has been included in the Cryogenic Materials Data Handbook to provide a general purpose reference for those working in the field of cryogenic testing. Typical examples of equipment and techniques used by various researchers are described. No attempt is made to present a complete description of each technique or to mention all those engaged in cryogenic testing and research.

In many cases, we have described the techniques used by the laboratories that provided data for handbook insert graphs.

I. TENSION TESTING

Tension tests can supply more useful information on the mechanical behavior of materials than any other single test. Information on elasticity, flow, fracture, and ductility properties can be obtained with a single specimen. At cryogenic temperatures, an important additional property -- toughness -- can be assessed by tensile loading. Toughness is commonly determined by notched tension testing.

Cryogenic testing techniques are much the same as those used at ambient or elevated temperatures. The obvious difference is in the environmental apparatus used to achieve desired temperatures. Although some cryostats incorporate vapor cooling, most equipment uses constant-temperature liquid baths.

During some initial investigations to obtain needed data, some investigators used rather simple cryostats and equipment. Generally, more sophisticated designs have since emerged.

An example of a simple cryostat is the double-walled, stainless steel, foam-insulated cryostat used by the NASA-Lewis Research Center for early liquid-hydrogen testing (Fig. 1) (37). A simple vacuum-insulated cryostat has been used by Pratt & Whitney (81). In this unit, a stressing cylinder eliminates the need for the lower specimen grip to extend through the cryostat. A commercial stainless steel dewar is placed over the stressing cylinder and attached to the machine crosshead (Fig. 2). The shortcomings of the two cryostats just mentioned, however, are their poor thermal performance and excessive hydrogen consumption.

Testing cryostats using both a vacuum jacket and liquid-nitrogen jacket are described by Battelle (13, 50) and General Dynamics/Astronautics (GD/A) (150). The Battelle unit, illustrated in Fig. 3, is a triple-wall stainless steel construction. The inner chamber containing the liquid hydrogen is concentrically insulated by a vacuum space, a liquid-nitrogen bath, and a felt sheet. The lower grip is designed to seal-through the chambers, using Teflon O-ring compression seals.

The GD/A cryostat is similarly constructed. An immersion-type heater is used to vaporize the liquid hydrogen when the tension test is completed. Hydrogen consumption is reported to be about 12 liters per test (Fig. 4).

Cryostats using static vacuum jackets are typified by a design of McClintock and Warren (151) and the units used by Martin-Denver and Aerojet-General Corporation (AGC). Designed to give excellent thermal performance, McClintock's cryostat is a small unit constructed from a commercial stainless steel dewar. The major modification to the dewar is the incorporation of a tension linkage through the vacuum space at the bottom of the cryostat. A stainless steel bellows and universal joint are welded to the bottom of the inner can, permitting specimen contraction and alignment. Below the universal joint, a stack of 0.0005-in.-thick washers is used to transmit load from the lower grip to the specimen. A stud connected to the universal joint supports the stack from below, and a retaining well attached to the lower stem restrains the top of the stack. Therefore, the stack is compressed as tension is applied to a specimen within the cryostat. The increased heat path caused by the numerous contact surfaces substantially reduces the heat conduction from the stem through the vacuum jacket. Liquid consumption of this cryostat, after precooling with liquid nitrogen, is about 2.5 liters of hydrogen (Fig. 5).

The cryostats used by Martin-Denver and AGC were designed to accomodate Keys' multiple linkage system (152). To accept the large linkage, the loading axis of the cryostat is eccentric. A bellows located near the bottom of the outer chamber self-aligns the cryostat during loading. Stacked compression washers are used to reduce thermal transfer through the bottom grip. Figure 6 shows this cryostat, which is designed for both tension and compression loads.

A recently designed tensile cryostat for use to -452°F with minimum cryogenic liquid consumption is reported by Reed (153). Unmodified commercial dewars are used. Since the dewars are not required to support a load, silvered glass dewars may be used when very low heat input is desired, such as when testing at -452°F. The load is transmitted to the test machine crosshead through a cylinder and cup (Fig. 7). The upper specimen grip attaches directly to the load cell. Two dewars are used for low-temperature testing. The outer liquid-nitrogen shield is filled only for testing to -452°F and for long tests at -423°F. The inner dewar is placed inside the larger container and held by styrofoam spacers. This cryostat design has been used by Rice et al. (122) at -452°F in testing aluminum alloys and by Narmco (114) down to -423°F in testing of glass reinforced plastics. By using loading cages, Narmco has used this cryostat for compression and flexure testing.

A unique cryostat has been used by Rocketdyne (3) to evaluate nonmetallic materials. This unit (Fig. 8) is designed for tensile and compressive loading. The test dewar is mechanically clamped to a tensile, compressive, or flexural base plate. The dewar is a single vacuum-jacketed flanged stainless steel unit containing the upper tension rod and an exhaust vent. Fill and purge lines are attached through the base plate. A rubber-asbestos gasket is used as a cold seal to join the dewar to the base.

Several laboratories have used vapor cryostats for mechanical property testing. The principal advantage of this technique is that variable temperature control is possible as compared to the few temperatures that can be obtained using constant temperature liquid baths. Variable temperature control permits the investigator to study materials behavior at specific temperatures of interest. As a result, certain phenomena, such as strength peaks, transition behavior, etc, can be more thoroughly researched. In some cases, laboratories not prepared to handle liquid hydrogen safely have used vapors from liquid helium to produce the temperature (-423°F) of liquid hydrogen.

At Westinghouse Research Laboratories two vapor systems were described to cover the temperature range 70°F to -452°F (Fig. 9). One system (154) used liquid helium as a refrigerant to obtain temperatures in the range -452°F to -320°F. A schematic diagram of the control system and cryostat is shown in Fig. 9. A second system (154) used liquid nitrogen to provide temperature control in the range -320°F to 70°F. Lucas and Cataldo (155) of NASA have described a similar liquid nitrogen vapor cryostat.

The variety of tensile specimen designs approximately equals the number of researchers performing cryogenic testing. Different cryostat designs, for example, lead to the variation in the grip section of test specimens. General attempts have been made, however, to approach appropriate standards for the test gage section of these specimens.

Most sheet specimens have been pin-loaded with a large-diameter pin. As a result of minute misalignments during loading, most thin-gage materials tend to fail through the pin hole. Doublers welded to each surface of the grip eliminate this problem by increasing the bearing width. Figures 10 and 11 present some typical sheet specimen designs used throughout the industry.

The most significant variation in test gage design has been for notched specimens. With the exception of those who use the NASA-recommended sharp-notch design (and are successful in machining this notch), almost every design is unique. To further complicate data reporting, different methods for calculating the stress concentration factor are advocated. General Dynamics/Astronautics has recently begun to report K_t values calculated with Peterson's and Neuber's techniques, as well as the K_t values calculated as $(a/r)^{\frac{1}{2}}$. General Dynamics/Astronautics' K_t values for their specimen configuration using these three methods are as follows: (1) $K_t\left[(a/r)^{\frac{1}{2}}\right] = 6.3$; (2) K_t [Peterson] = 7.2; and (3) K_t [Neuber] = 7.5.

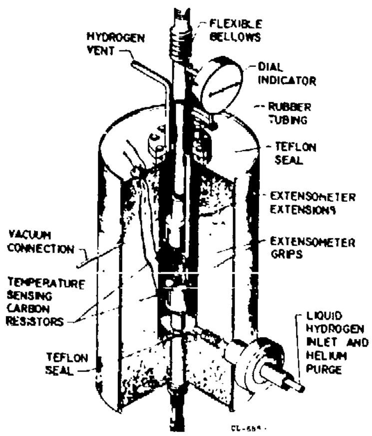


Fig. 1 Foam-Insulated Cryostat (NASA-Lewis)

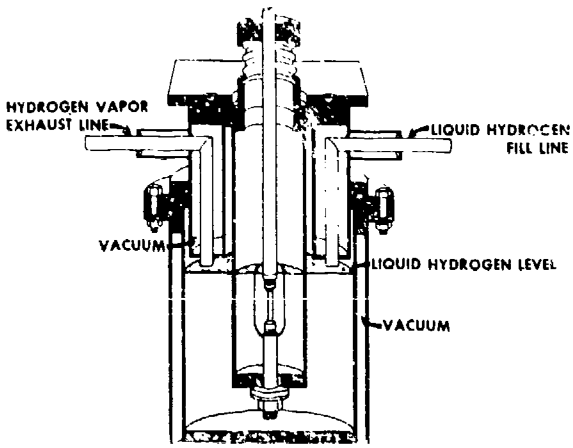


Fig. 2 Simple Vacuum-Insulated Cryostat (Pratt and Whitney)

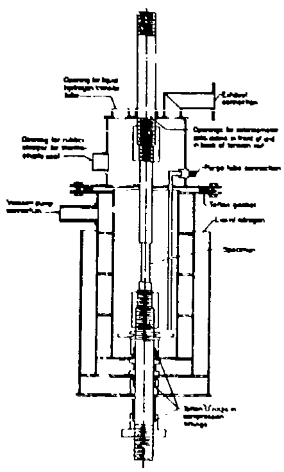


Fig. 3 Vacuum- and Nitrogen-Insulted Cryostat (Battelle)

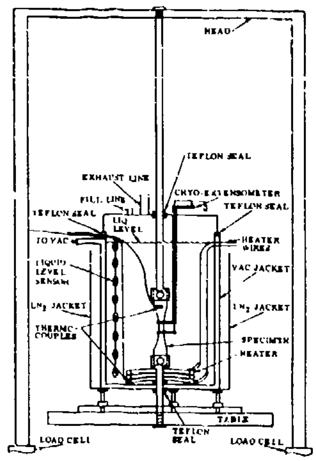


Fig. 4 Vacuum- and Nitrogen-Insulated Cryostat (GD/A)

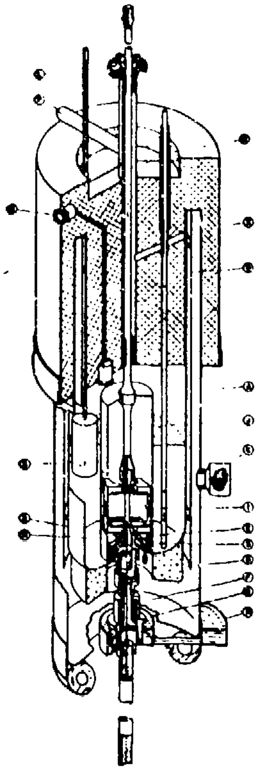


Fig. 5 Vacuum-Insulated Cryostat Using Modified Dewar (NBS)

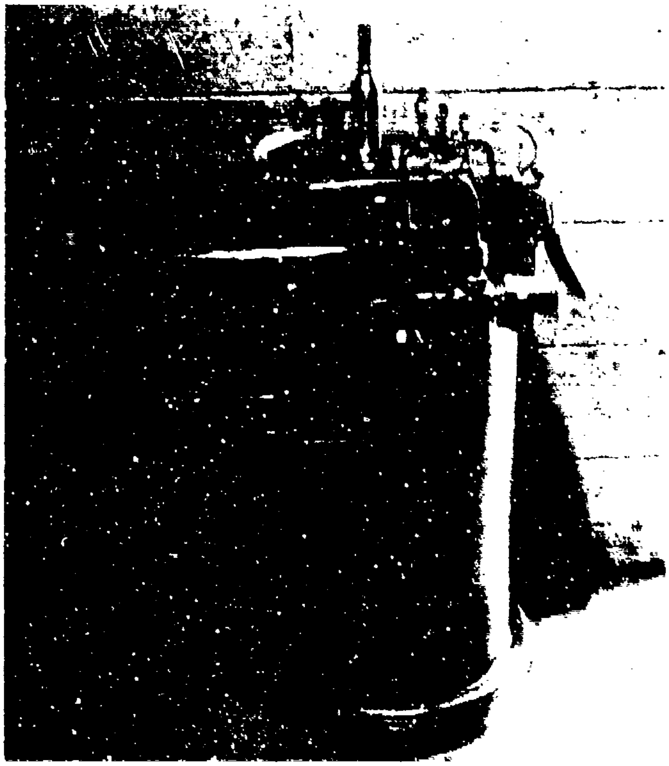


Fig. 6 Large Vacuum-Insulated Cryostat (Martin-Denver)

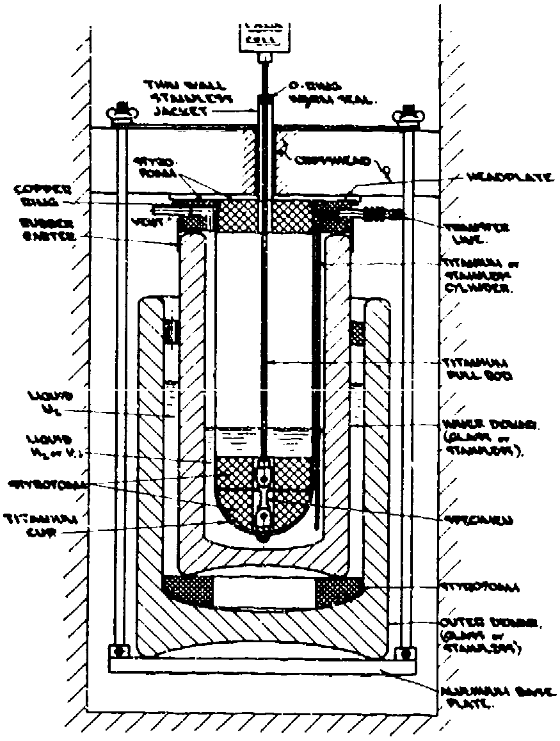
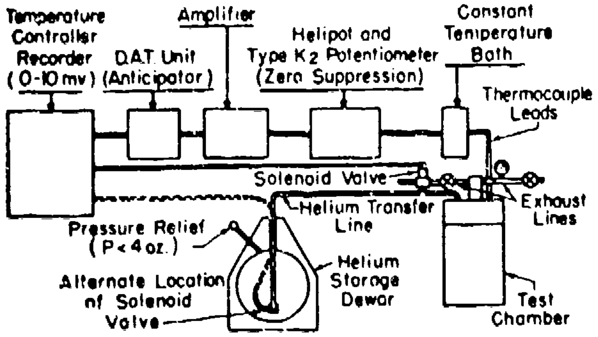
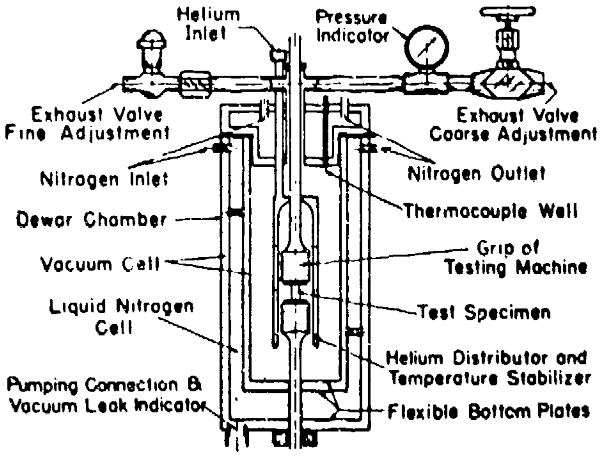


Fig. 7 Vacuum- and Nitrogen-Insulated Cryostat Using Loading Cylinder (NBS)

Fig. 8 Vacuum Insulated Cryostat for Non-Metals Testing. (Rocketdyne)



a. Control Diagram



b. Vapor Cryostat

Fig. 9 Liquid Helium Vapor Cryostat (Westinghouse)

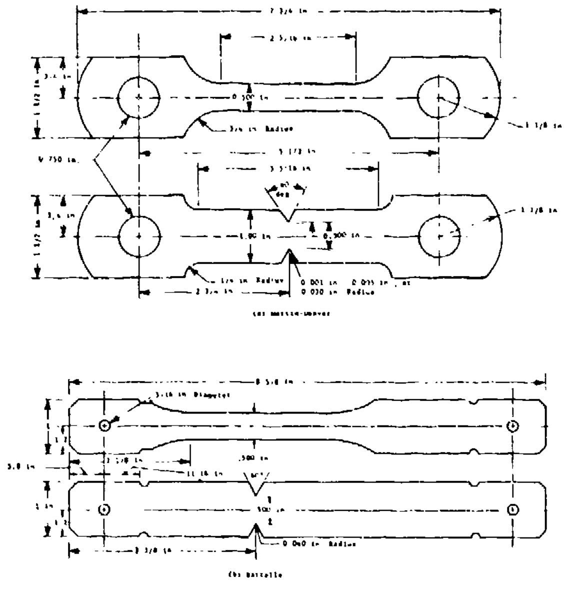


Fig. 10 Typical Sheet Specimen Designs (Martin-Denver and Battelle)

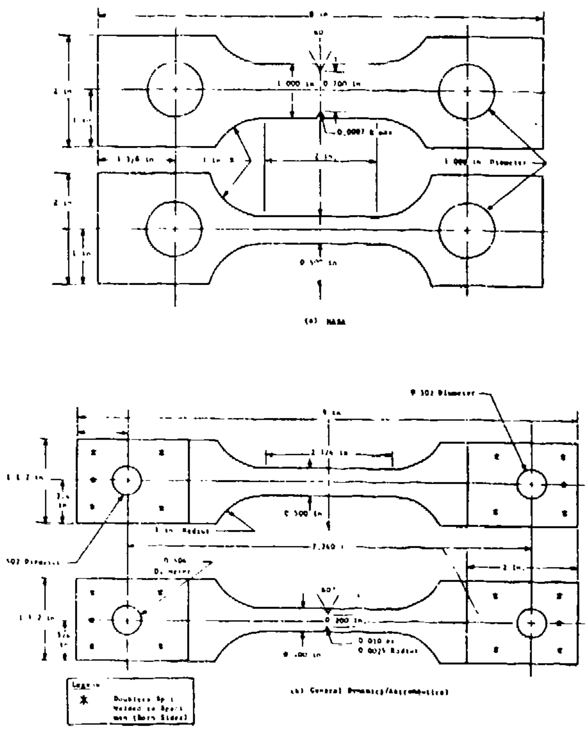


Fig. 11 Typical Sheet Specimen Designs (NASA and GD/A)

II. IMPACT TESTING

Impact testing down to -320°F has been routinely accomplished by many laboratories. The typical procedure has been the transfer of a specimen, with tongs, from a liquid bath to the test machine anvil, where it is quickly tested.

Because of the very low thermal capacity $\left(C_p\right)$ of metals at cryogenic temperatures, virtually no surface condensation of gases, convective heat transfer, or conductive heat transfer, can be permitted without a rapid increase in specimen temperature. Testing with liquid hydrogen exposed to air is both thermally inefficient and potentially dangerous. However, early evaluations of materials at -423°F were performed at Ohio State University (30, 32) and Battelle (Ref 13), using direct transfer of specimens in air from an open-mouth dewar. The specimens were lifted by threads (Fig. 12) and were paper-wrapped to retain some liquid hydrogen around the specimen surface to delay temperature rise. No attempts were made to determine temperature rise before impact.

A concept of the National Bureau of Standards (Cryogenic Engineering Laboratories) presents a more sophisticated approach to impact testing at or below -423°F. A cryostat is used to cool impact bars in a tight-fitting chamber. A push-rod inserted in one end of the chamber feeds specimens dropped from a supply magazine directly onto the anvil of the test machine. However, condensation in the chamber and the subsequent temperature rise from heat of vaporization and fusion of atmospheric gas might be a potential problem for this apparatus.

A relatively complicated machine for impact testing has been described by DeSisto of Watertown Arsenal (61). The test apparatus consists of an evacuated enclosure that houses a complete Charpy impact machine, storage drum, cold box, cooling mechanism, and automatic cycling device.

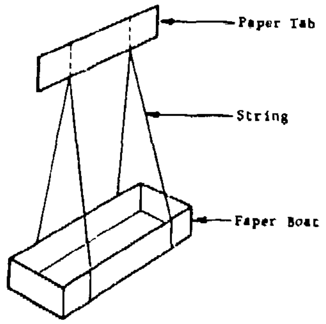


Fig. 12 Schematic Diagram of Paper Boat Transfer Method (Ohio State University)

Figure 13 shows a diagram of the feed system for this machine. The storage drum accommodates 100 impact bars. With specimens in the cold box, a total of 105 specimens can be stored. Since convection and radiation cooling cannot be used, conduction cooling is required. The cooling mechanism uses jaws loaded at 50 lb to ensure intimate contact for conduction between the specimens and the cooling surfaces. The refrigerant, liquid helium, is metered to achieve continuous temperature control down to -445°F. Depression of a starter button will start the automatic test cycling mechanism when specimens are cooled. Advantages of this system are temperature control versatility, freedom from condensation heat transfer effects, and freedom from liquid hydrogen hazards. Disadvantages are equipment cost, complexity, and a relatively low rate of testing.

Another approach to impact testing is that used by Rocketdyne. For -423°F impact testing of nonmetallics, a jacketed vacuum-insulated container with an O-ring seal is placed over the impact anvil, and specimen sealing is placed against a polished base (Fig. 14). After filling with liquid hydrogen, the container is quickly removed and the hammer released. Rocketdyne has restricted this testing to nonmetallics. Although no attempt has been made to preclude condensation problems, a rapid testing sequence should minimize temperature rise.

Martin (156) has taken the advantages of several systems and combined them in a simple, safe impact testing system. The access and simplicity of the open-air transfer method is combined with the thermal performance of the more complicated Watertown method, although it limits test temperatures to those attainable with liquid baths. A glove box enclosure is used to house an entire impact machine. An internal helium atmosphere is used to prevent gaseous condensation. Liquid hydrogen is contained within the enclosure in an open-mouth dewar for use as a specimen cooling bath (Fig. 15).

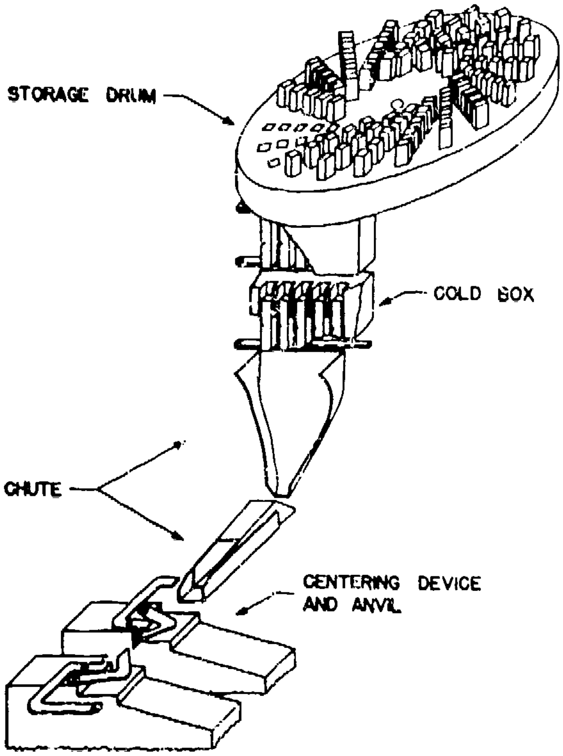


Fig. 13 Feed System for Waterton Impact Machine

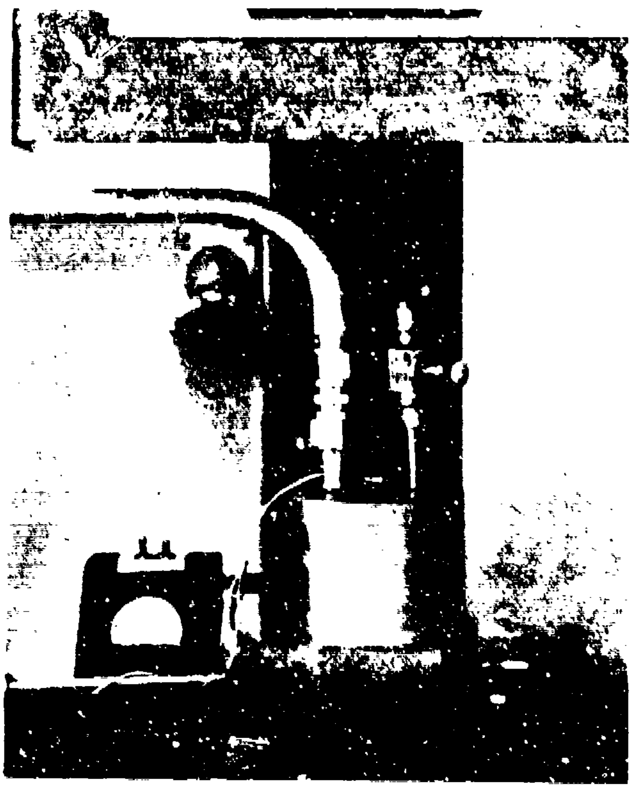


Fig. 14 Vacuum-Jacketed Dewar Used for Izod Testing (Rocketdyne)

Fig. 15 Inert Gas Chamber for Impact Test Machine (Martin-Denver)

III. FATIGUE TESTING

Fatigue tests are best described by discussion of the methods used to apply loads. Tests are conducted by (1) repeated loading to a constant stress amplitude, and (2) repeated loading to a constant strain amplitude. The former method is obtained by direct axial loading. The latter can be best achieved by bending techniques, either plane bending or rotational bending.

In axial loading, the entire cross section is uniformly loaded. Stress is therefore determined by the familiar relationship of load/area. In reversed bending, the stress varies throughout the cross section of the test specimen, from a maximum at the outer fiber through zero at the neutral axis to a maximum value at the opposite outer surface. Using this technique, stress must be obtained by calculation from the moment formula.

$$S = Mc/I$$

Although bending tests, both rotational and plane, have been the most popular fatigue techniques in past years, they are currently being replaced by the axial-load method. Certain disadvantages associated with bending fatigue tests have favored this change.

As shown by the formula above, stress in bending is obtained by calculation using the bending moment and section modulus. The bending moment M is a function of the modulus of elasticity of the test material. Although moduli of common engineering materials are well known at room temperature, little information is available at cryogenic temperatures.

An early evaluation cryogenic fatigue behavior was conducted at Ohio State University (12, 30, 31) down to -320°F. Constant deflection Krouse reciprocating-cantilever-beam machines were modified so that the specimens was positioned in a vertical rather than horizontal plane. A split metal dewar was used to surround the specimen.

A recent evaluation by the repeated-bending technique was performed by Battelle at temperatures to -423°F (4, 5). For testing at cryogenic temperatures, conventional cam-operated reversed-bending machines were modified by extending the fixed specimen grip and drive shaft sufficiently to allow the test specimen to be cooled in a constant temperature bath. A thin-walled 2-in.-diameter tube was used to support the fixed end of the specimen (Fig. 16).

For operation at -110 and -320°F, a glass dewar was raised into position surrounding the specimens. At -423°F, two stainless steel double-walled vacuum dewars, mounted one within the other, were used. These dewars were commercially available and used without modification. To reduce the consumption of liquid hydrogen, a belt and pulley arrangement was constructed to allow operation at 5175 cps, three times normal machine speed. Thus the time for a million-cycle experiment is reduced to only slightly more than 3 hr.

The bending approach requires a minimum of modification to test equipment and uses inexpensive fixtures and accessories. Testing speed can be easily increased to reduce the use of liquid hydrogen. In the Battelle program, the absence of modulus values for several alloys prevented presentation of all of the data in the form of S/N curves.

Sheet alloys are currently being axially tested at Martin-Denver (15, 168). The cryostat assembly is attached between the platens much the same as a room-temperature specimen. The cryostat design calls for a double-walled stainless steel vacuum dewar with a tubular support base to minimize thermal transfer from the bottom specimen grip. The base must have sufficient rigidity to support test specimens under maximum cyclic loading. The cryostat is secured to the reciprocating platen by a self-aligning mounting fixture that can be rapidly disassembled. A base block, screwed to the cryostat base, slides into a precision-ground slot in a retainer block bolted to the lower platen, and wedge plates lock the entire assembly. The cryostat lid, containing the transfer line, vent, and level sensor probes, is mounted to the head frame with another base block, retainer block, and wedge plate assembly. A flexible seal joins the cryostat and lid to preclude air pumping. The level sensor used for this equipment is designed to achieve automatic fill. An unusual feature of this effort is that complete stress reversal (tension-compression) tests are being performed on sheet gage (0.100 in.) material. Normally, tension-compression testing is restricted to bar specimens. The requirement for reversed stressing justifies the precision alignment fixtures described above. The axial-load technique clearly requires more effort that the bending approach. Although no equipment modification is necessary, the cryostat and accessories require very careful design. Unlike the dewar in the bending apparatus, the axial-load cryostat is vibrating at the machine speed (1800 cpm for the SF-10U machine used in this work). Because of difficulty in increasing the speed of axial-load machines, equipment designed for low liquid consumption during tests in the 10^6 to 10^7 cycle range is desired. Figure 17 shows a cutaway view of the cryostat.

High-stress, low-cycle fatigue tests have been conducted by GD/A (10) on complex welded joints at temperatures from 70° to -423°F. Axial loading was performed with hydraulic rams at a rate of 6 cpm. Figure 18 shows a specimen installed in the cryostat.

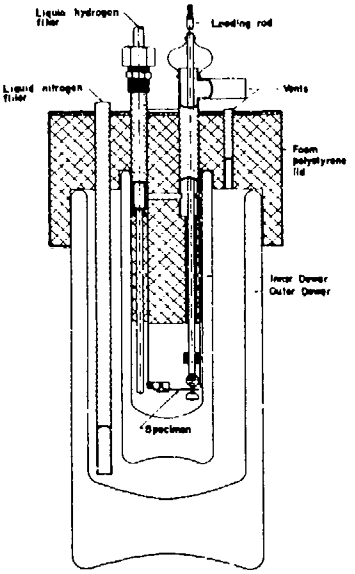


Fig. 16 Bending Fatigue Apparatus for -423°F (Battelle)

Fig. 17 Cutaway View of Axial Load Cryostat (Martin)

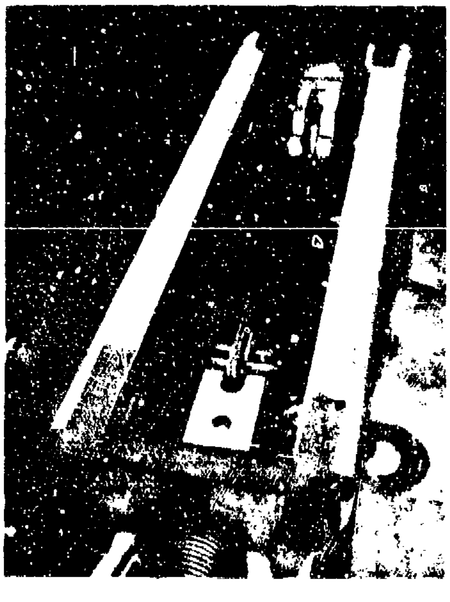


Fig. 18 Low-Cycle Fatigue Apparatus (GD/A)

IV. HARDNESS TESTING

Hardness determination has been used as a simple method for estimating or predicting strength properties of a material. Considerable work has been performed in evaluating hot hardness and correlating it with strength properties at elevated temperatures. The basis for this work can be found in the definition of hardness: resistance to deformation under an applied load. This definition indicates a strength test. The units of hardness (applied load or force divided by area of indentation) are the units of stress.

The hardness test can be used at cryogenic temperatures as well as it has been performed at elevated temperatures. A simple apparatus for cryogenic hardness testing used by Battelle (13) is shown in Fig. 19. Hardness specimens were clamped to a small stage suspended in an open-mouth stainless steel dewar. Hardness indentations are made at cryogenic temperatures and then read at ambient temperature. As indicated, this unit used constant-temperature liquid baths. Similar equipment has been used at Ohio State University (30, 32) for testing down to -320°F.

A vapor cryostat to obtain continuous variable temperatures, has been constructed by Westinghouse (157). The agreement between hardness and strength properties of columbium at the subzero temperatures is very good.

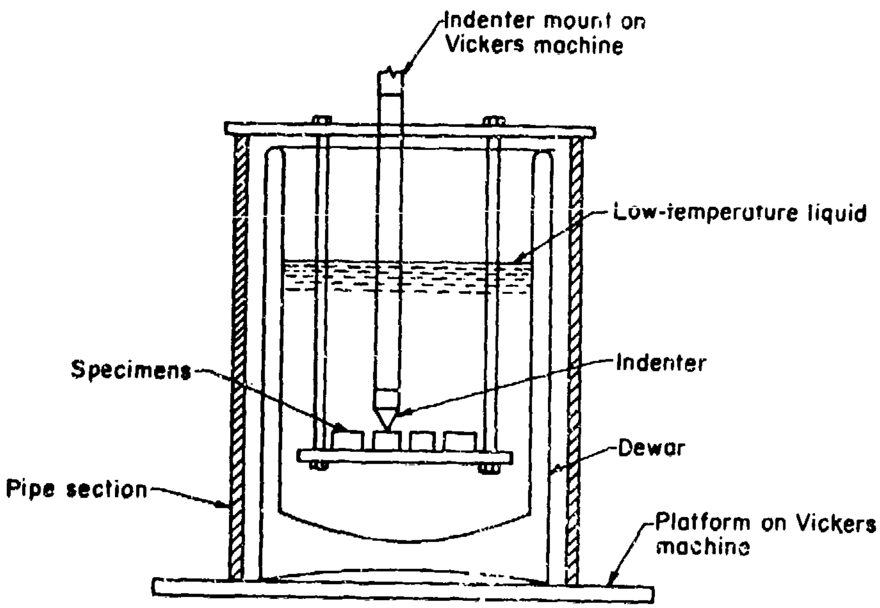


Fig. 19 Hardness Cryostat (Battelle)

V. FRACTURE TOUGHNESS

Fracture toughness testing has been performed by several laboratories down to -423°F. The techniques for cryogenic testing are much the same as those used for testing of conventional tensile specimens. The principal differences are: (1) generally larger and often thicker specimens, and (2) crack growth measurements or compliance measurements are frequently made.

General Dynamics/Astronautics (46, 179) has tested center notched specimens of thin gage sheet metals from 2 to 18 in. in width. They use a large windowed cryostat that can accommodate specimens as large as 18-in. wide and 36-in. long (Fig. 20). The window consists of three layers of plexiglass. The procedure for testing is to attach a steel scale to the specimen adjacent and parallel to the center notch. Two telescopes (with vertical cross-hairs) are used to measure the crack size. One scope is focused on each tip of the crack. Tensile loads are applied to the specimen while readings of crack length are continually made through the telescopes. Critical crack length is defined as the longest measured crack observed prior to the onset of rapid fracture. Because of the thin gage of the materials evaluated and

Fig. 20 Crack Propagation Cryostat (GD/A)

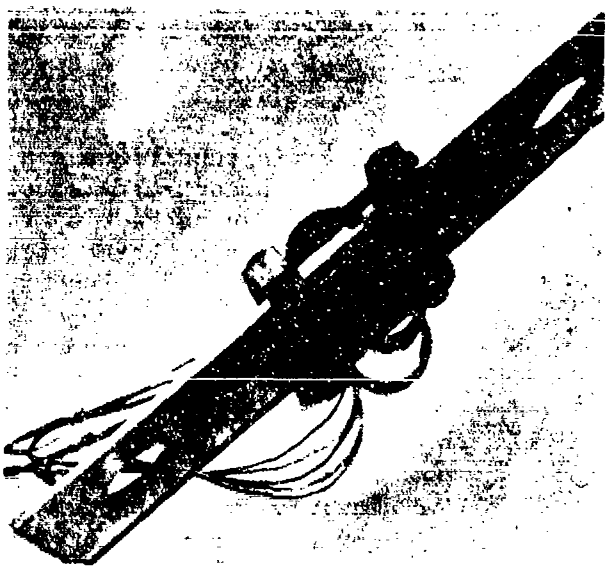


Fig. 21 Strain Beam Compliance Gage (Martin)

to reduce lateral buckling, doublers were welded to the grip portions of the 2- and 4-in. specimens. Larger specimens (8- to 18-in. wide) were fitted with end clevises containing multiple bolt holes to provide clamping action. Center notches were prepared by electric discharge machining with a tip radius not exceeding 0.001 in.

Martin-Denver (1) has also tested narrow center notch specimens of thin gage sheet metals. Unlike the GD/A work, a compliance gage was used to obtain crack extension measurements. Use of this gage obviates the necessity for a windowed cryostat and its attendant problems of crazing, frosting, and poor thermal performance. The compliance gage (shown in Fig. 21) uses a strain beam instrumented with Nichrome V foil gages. A compliance calibration was obtained using the Westergaard method described by Boyle.* Test specimens contained fatigue-extended cracks and were reinforced at the grip ends with welded doublers to reduce lateral buckling and prevent bearing failures.

Surface cracked and notched round bar specimens used to obtain plane strain data are ideally suited for cryogenic testing because they do not require crack extension instrumentation. To determine toughness, fracture load and initial crack size are all that are necessary. The problem with notched round bar specimens frequently is the high loads required to attain low strength fracture in tougher materials. Few laboratories are equipped with test machines and cryostats suitable for the loads frequently required. The surface cracked specimen is becoming very popular and is readily adaptable for cryogenic testing because plane strain conditions can be achieved with a thinner section than with through-cracked specimens. Therefore, the load requirements can be kept to reasonable levels. Notch round bar data are found in References 181 thru 184. Surface cracked data are contained in References 175, 180, 184, 185 and 186.

The use of single-edge notch specimens at cryogenic temperature has been rather limited. Carman (175, 180) has evaluated SEN specimens down to -423°F. Instrumentation required for this type of testing is a "pop-in" gage located across the notch. For thinner gages of tough materials, the gage requires a high level of sensitivity for detection of "pop-in" load used in calculation of plane-strain fracture toughness.

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*R. W. Boyle: "A Method for Determining Crack Growth in Notched Sheet Specimens." Materials Research and Standards, p 646, August 1962.

VI. TORSION TESTING

A torsion apparatus for measuring shear modulus of metals from 70 to -423°F has been described by Mikesell and McClintock (158). The specimen is secured to two concentric stainless steel cylinders, as shown in Fig. 22. The outer cylinder is stationary. A couple is applied to the inner cylinder by weights placed on pans. Pulleys transform the vertical force from the weights to a horizontal force. Using a mirror and light-beam lever, twist of the specimen is measured by observing the displacement of an image. Test results showed good reproducibility and close agreement with published room-temperature data. Data obtained by this device would be particularly useful in calculating Poisson's ratio using the following relationship:

$$G = \frac{E}{2(1 + \mu)}$$

where G is the shear modulus or modulus of rigidity, E is the modulus of elasticity (Young's modulus), and μ is Poisson's ratio.

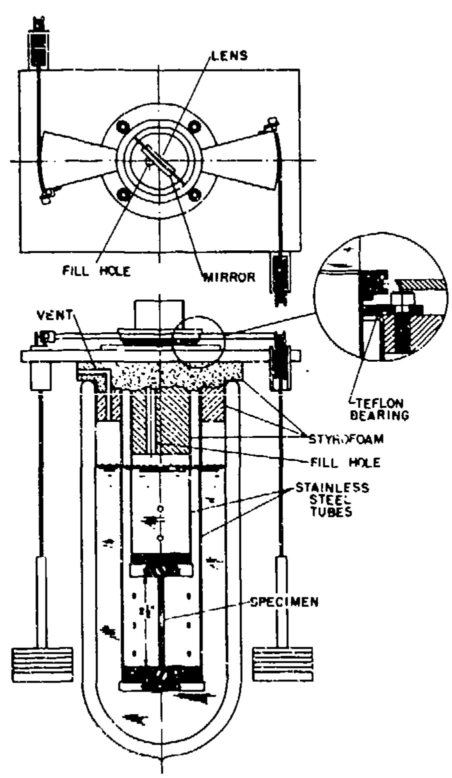

Fig. 22 Torsion Tester (NBS)

During the past few years, a great deal of interest in testing glass-reinforced plastic materials down to -423°F has been created. Fortunately, testing of nonmetallic materials can generally be performed in the same equipment used for metals testing. Evaluating reinforced plastics requires more flexural and compression loading than metallic materials. However, carefully designed experiments will permit performance in the normal apparatus. Specimen design is the principal problem associated with nonmetallics testing.

Tensile specimens present a problem because pin-loaded specimens tend to fracture through the pin holes. Solutions to this problem have been grip reinforcement of pin loaded specimens (114), large ratio of grip/gage width for pinned bars (1), and clamping jaws (171).

Flexural testing has been performed by both tension and compression loading. Narmco (114) uses tension loading through a cage arrangement since their cryostat is not designed to accommodate compressive loads. Martin uses compressive loading in a multiple testing apparatus (see Fig. 28).

Compression testing has also been performed using tension or compression loading. Narmco (114) uses a compression cage. Martin uses a subpress to assure precision alignment and a rotating plate to provide multiple testing capability (see Fig. 29).

Naval Ordnance Laboratory (NOL) rings have been tested down to -423°F by Martin for this handbook. Testing is performed in accordance with the recently approved ASTM method.

Thermal expansion measurements down to -454°F have generally been performed using a quartz-tube dilatometer with a dial gage as the measuring device. A variety of these units are described in the literature (21, 25, 47, 69, 159). Figure 23 shows a typical unit, used by The National Bureau of Standards, Cryogenic Engineering Laboratories.

Several laboratories have used the interferometric method for more precise thermal expansion measurements (26, 161).

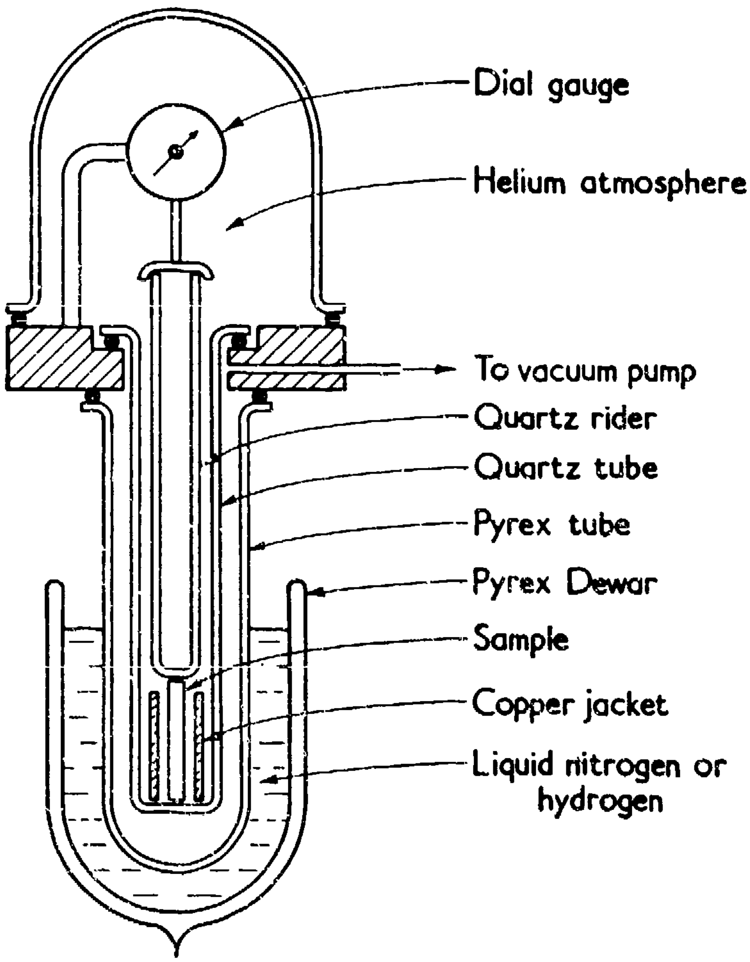

Fig. 23 Cryogenic Dilatometer (NBS)

IX. STRAIN MEASUREMENTS

Accurate determination of strain has been one of the major problems in the evaluation of materials at cryogenic temperatures. Strain measuremens have been obtained by two instruments: separable mechanical extensometers, and resistance strain gages.

Mechanical extensometers can be constructed with either the transducing elements removed from the cryostat or installed in the cryogenic media. Extensometers of the former type are basically similar to high-temperature units that use arms to transmit strain to an external sensing device. A simple unit using a dial gage to read strain has been used by NASA-Lewis (37). Figure 1 shows this unit installed in their testing cryostat.

For more precise strain readings and automatic recording, a differential transformer or strain gage beam is required. The extensometer used by GD/A (Fig. 24) is of this type. A differential transformer is used to convert strain to an electrical signal. Care should be taken to design mechanical extensometers so that errors due to bending of sheet materials are minimized. An averaging-type extensometer using dual extension arms and transducing elements will cancel errors due to bending. Testing at Battelle has been performed with such a unit using a Baldwin PSH-8M high-temperature, averaging, microformer extensometer for the liquid-hydrogen studies (13, 50). For cryogenic operation, the unit was inverted from its normal position so that the extension rods would emerge from the lid of the cryostat.

The principal shortcomings of an extended arm extensometer are heat loss through the arms, and errors inherent in such a mechanical linkage system. The obvious solution to the problems associated with extension-type units is complete immersion in the cryogenic environment. The National Bureau of Standards (151) uses an immersed averaging-type extensometer with dual strain gage beams.

Lockheed Nuclear Products (162) reports the use of a differential transformer extensometer at cryogenic temperatures in the presence of nuclear radiation. The differential transformer is radiation-resistant. The extensometer was calibrated with a Tuckerman optical strain gage.

The alternative to mechanical extensometers is the use of resistance strain gages connected directly to the specimen. Strain gages have been used in the materials research program conducted by Martin-Denver. Foil-type gages are bonded to flat specimens using epoxy and polyurethane adhesives. Although strain gages have been used quite successfully at cryogenic temperatures, considerable care is required in their application and use. To avoid the problems usually associated with bridge balancing and temperature compensation, the entire bridge is immersed in the cryogenic liquid. The remaining two or three legs (depending on whether one or two active legs are used) of the bridge circuit consist of strain gages bonded to a sheet of the material to be evaluated. Load-strain curves giving a total strain of at least 20,000 micro-inches are attainable with a proper combination of gage and adhesive.

To use the strain gages at temperatures other than ambient, they must be calibrated for the change in gage factor (or strain sensitivity) with temperature. The calibration technique involves determining the characteristics of the gage under known strain at various temperatures. Strain gage calibrators constructed by McClintock (163) and Chiarito (164) use the principle of the constant strain cantilever beam. The width of a cantilever beam of constant thickness can be varied so that the strain is constant along its length, except at the extremities where attachments are made. To produce strains, the beam is deflected to various known levels. In operation, strain gages are bonded to the constant strain portion of the beam and various deflections are applied. Resistance of the gage is accurately determined before straining and in the strained condition. This operation is repeated at various temperatures.

Strain sensitivity or gage factor is defined as

$$k = \Delta R/R\epsilon$$

where ϵ is the strain and R is the resistance.

The NASA calibrator is depicted in Fig. 25. A simpler type of calibrator has been developed by Keys (152), in which a spring reed device is bent to a constant curvature. Gage factor change is determined as before, except that it is first necessary to calculate strain using the manufacturer's reported room temperature gage factor. For calibration at cryogenic temperatures, the calculated strain value and experimentally determined resistance values are used. The obvious shortcomings of the device is that it is not absolute, since it is necessary to rely on the reported gage factor, which may be inaccurate.

Evaluations of strain gages for cryogenic service have been performed extensively at NASA-Lewis (164, 166, 167). The evaluations have shown that Nichrome V and Armour D are the most desirable materials for liquid hydrogen service.

X. MULTIPLE SPECIMEN TESTING

Mechanical property tests of materials in liquid hydrogen are usually accomplished in a rather slow and involved manner when compared with similar tests done at room temperature. This slow procedure is due mostly to the requirement to remove all air from the cryostat before transferring liquid hydrogen. The time spent in testing a specimen in liquid hydrogen amounts to only a fraction of the total time involved in conducting such a test. Most of the test time is spent on "conditioning" the test chamber; that is, the sealing, evacuating, purging, filling, emptying, warming, and re-opening necessary with liquid hydrogen testing.

One way to save time during such a test routine is to perform several tests in sequence, requiring only one filling. In this way the liquid hydrogen is handled in the usual manner but far less frequently, thus reducing time and costs. When testing is performed in a combined environment of cryogenic bath and nuclear radiation, the requirement for multiple testing becomes even more critical.

Martin (152) developed a system for testing of six sheet tensile specimens at a single filling of the cryostat. Figure 26 shows the start of the testing sequence (cryostat omitted).

General Dynamics/Astronautics (169) used a multiple specimen testing arrangement for tensile evaluation in a nuclear field. The test specimens contained elongated holes at one end so that only one specimen at a time was stressed (Fig. 27).

Multiple flexure and compression testing of glass-reinforced plastic laminates has been used for cryogenic testing by Martin to obtain data for this handbook. Figures 28 and 29 show the flexure and compression test devices, respectively. A cartridge is used to store ten flexural specimens. A rotating plate is used to hold six compression specimens. Double pin shear testing using a multiple testing device was recently reported by AGC (170). This device, designed for use in a nuclear field, uses a slotted blade arrangement, as shown in Fig. 30. Although the span width varies, the authors reported no significant differences in properties.

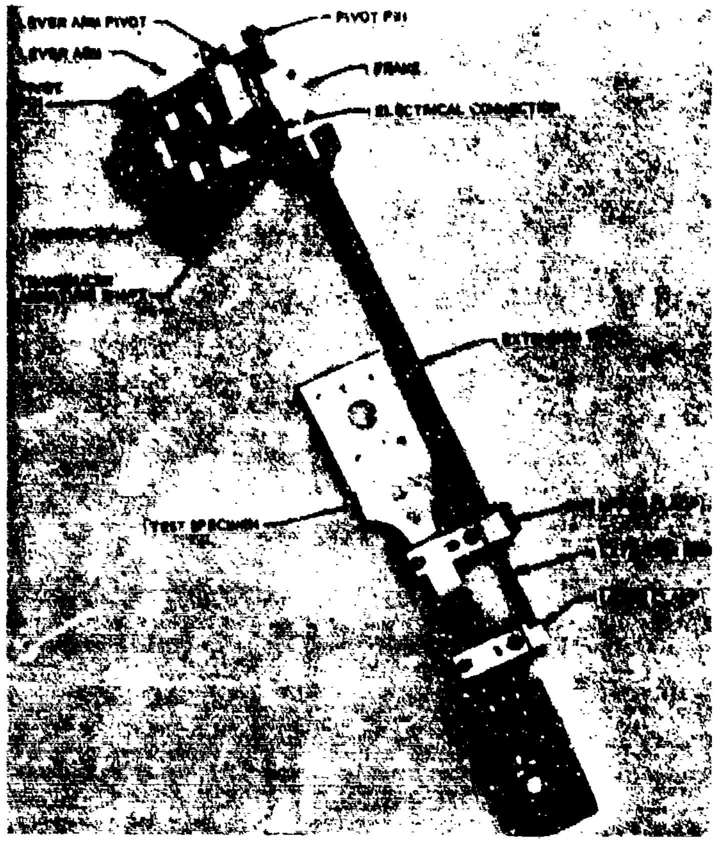

Fig. 24 Differential Transformer Extensometer (GD/A)

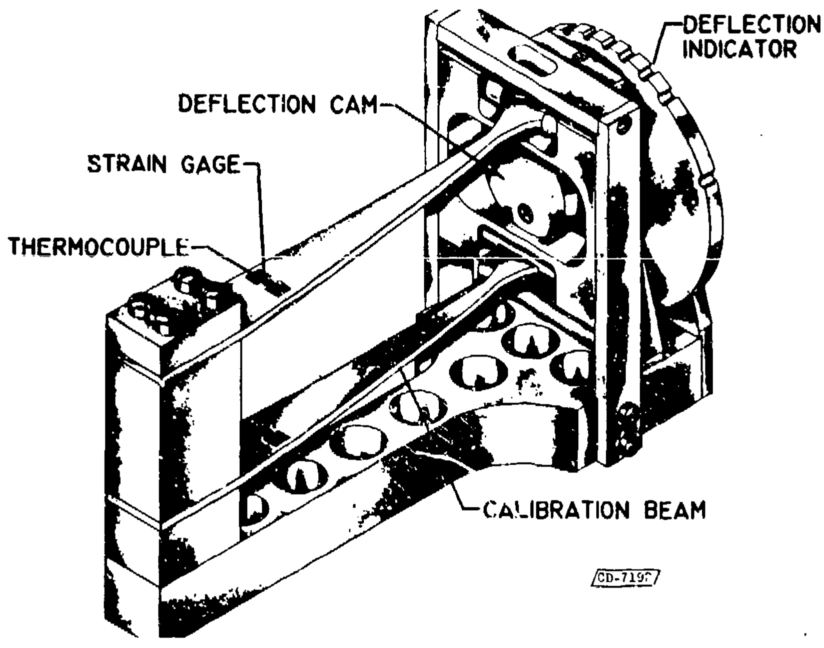

Fig. 25 Strain Gage Calibrator (NASA)

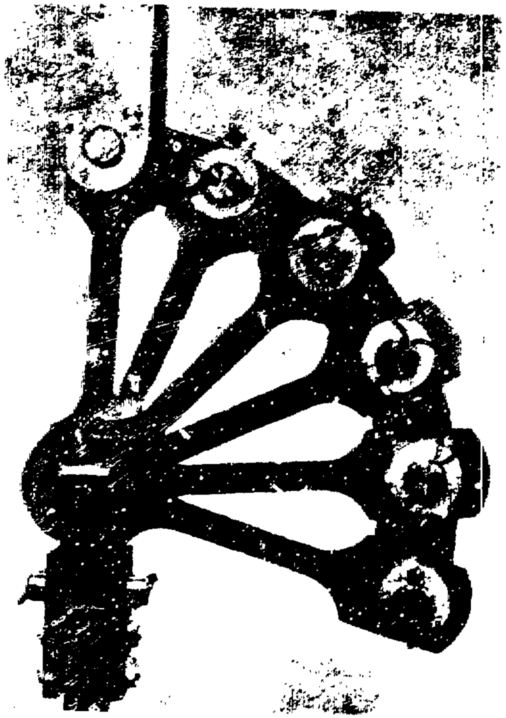

Fig. 26 Multiple Linkage System for Tension Testing (Martin)

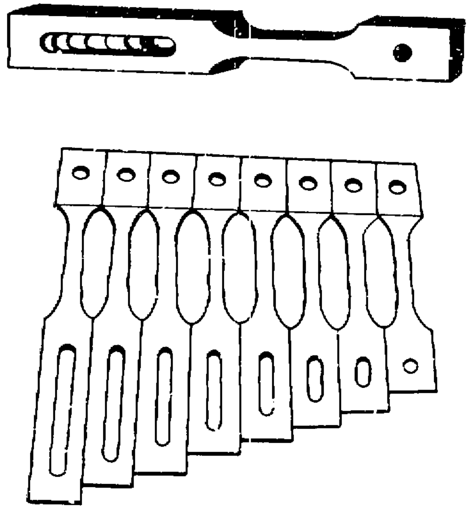

Fig. 27 Multiple Tensile Specimen Arrangement (GD/A)

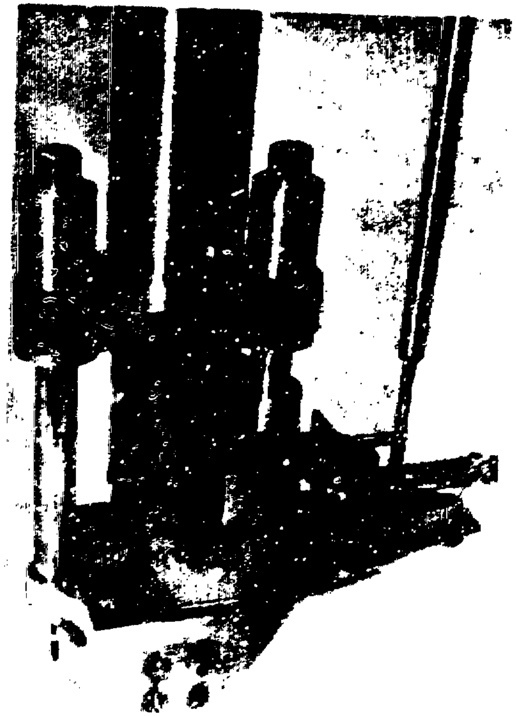

Fig. 28 Multiple Flexure Testing Device (Martin)

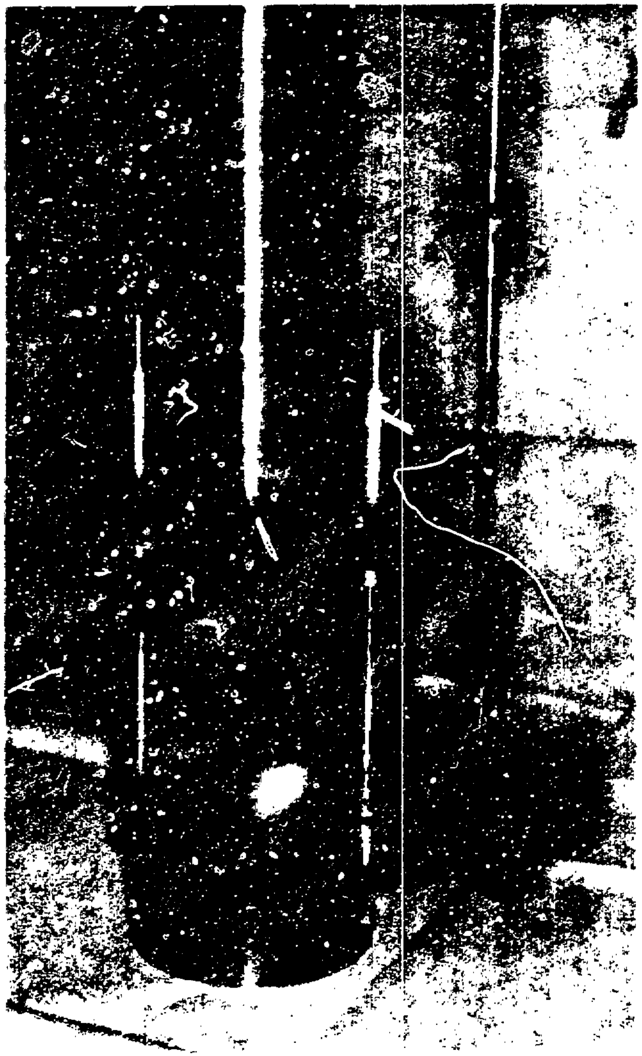

Fig. 29 Multiple Compression Testing Device (Martin)

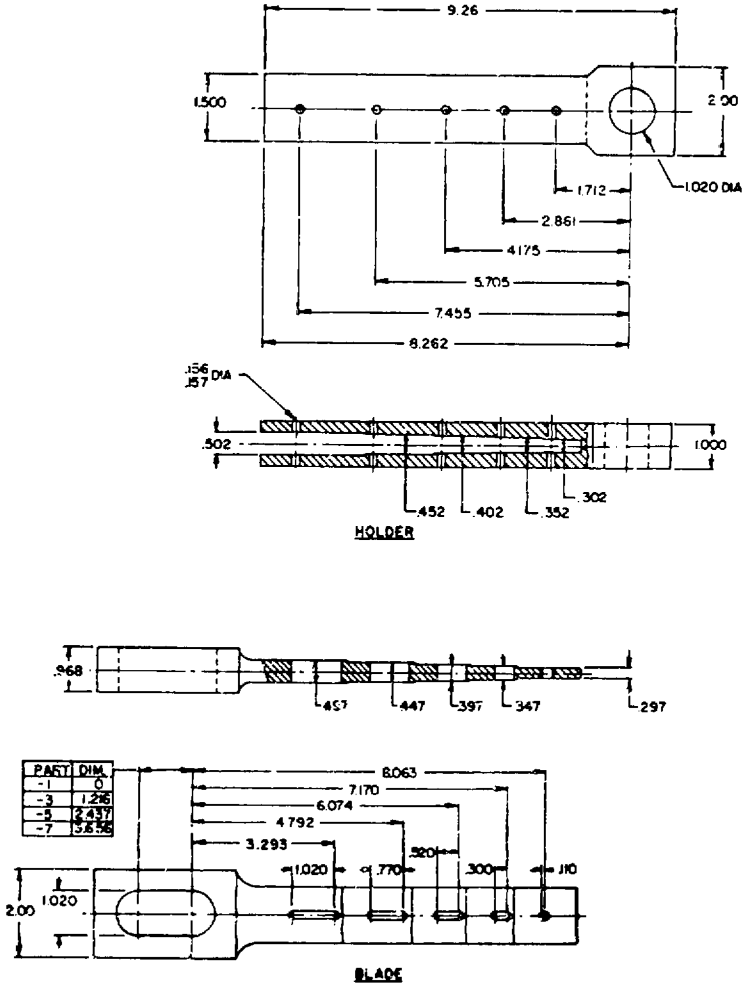

Fig. 30 Multiple Double Pin Shear Specimen (AGC)

REFERENCES

REFERENCES

1. Data obtained for Cryogenic Materials Data Handbook by Martin Company, Denver, Colorado, under Air Force contract AF33(657)-9161.

2. K. A. Warren and R. P. Reed: Tensile and Impact Properties of Selected Materials from 20 to 300°K. Monograph 63. National Bureau of Standards, June 1963.

3. R. E. Mowers: Program of Testing Nonmetallic Materials at Cryogenic Temperatures, Final Report. RTD-TDR-63-11. Rocketdyne, December 1962.

4. R. J. Favor et al.: Investigation of Fatigue Behavior of Certain Alloys in the Temperature Range of Room Temperature to -423°F. WADD TR 60-123. Battelle Memorial Institute, June 1961.

5. D. N. Gideon et al.: Investigation of Notch Fatigue Behavior of Certain Alloys in the Temperature Range of Room Temperature to -423°F. ADS-TDR-62-351. Battelle Memorial Institute, April 1962.

6. Data obtained for Cryogenic Materials Data Handbook by Cryogenic Engineering Laboratories, National Bureau of Standards, under Air Force contract AF04(647)-59-3.

9. J. F. Watson and J. L. Christian: Low Temperature Properties of Cold Rolled AISI Types 301, 302, 304L, and 310 Stainless Steel Sheet. Spec. Tech. Pub. 287. ASTM, 1960, p 170 thru 193.

10. J. L. Christian: Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment. ASD-TDR-62-258. General Dynamics/Astronautics, March 1962.

11. J. F. Watson et al.: Selection of Materials for Cryogenic Applications in Missiles and Aerospace Vehicles. MRG-132. Convair/Astronautics, February 1960.

12. J. W. Spretnak et al.: "Notched and Unnotched Tensile and Fatigue Properties of Ten Engineering Alloys at 25°C and -196°C." Trans. Am. Soc. Metals, Vol 43, 1951, p 547.

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13. R. L. McGee et al.: The Mechanical Properties of Certain Aircraft Structural Metals at Very Low Temperatures. WADC TR 58-336. Battelle Memorial Institute, November 1958.

14. J. L. Christian: Mechanical Properties of Titanium and Titanium Alloys at Cryogenic Temperatures. MRG-189. Convair/Astronautics, October 1960.

15. F. R. Schwartzberg et al.: Determination of Low Temperature Fatigue Properties of Aluminum and Titanium Alloys, Annual Summary Report. Martin Company, Denver, Colorado, July 1963. Prepared under NASA contract NAS8-2631.

16. R. P. Mikesell and R. P. Reed: The Results of the Impact Testing of Copper Alloys. Memo AT(29-1)-1500. Report to US Atomic Energy Commission. Cryogenic Engineering Laboratories, National Bureau of Standards, 1958.

17. V. N. Krivobok and A. M. Talbot: "Effect of Temperature on the Mechanical Properties, Characteristics, and Processing of Austenitic Stainless Steels." Proc. Am. Soc. Testing Materials, Vol 50, 1950, p 895.

18. R. H. Kropschot et al.: Low Temperature Tensile Testing Equipment and Results (300-20°K). Report 2708. Cryogenic Engineering Laboratories, National Bureau of Standards, July 1953.

19. E. T. Wessel: "Some Exploratory Observations of the Tensile Properties of Metals at Very Low Temperatures." Trans. Am. Soc. Metals, Vol 49, 1957, p 149.

20. V. N. Krivobok and R. D. Thomas, Jr: "Impact Tests of Welded Austenitic Stainless Steels." Welding J. Research Supplement, September 1950.

21. V. Arp et al.: "Thermal Expansion of Some Engineering Materials from 20 to 293°K." Cryogenics, Vol 2, No. 4, June 1962.

22. R. A. Baughman: Gas Atmosphere Effects on Materials. WADC TR 59-511. General Electric Co, May 1960.

23. J. Dyment and H. Ziebland: The Tensile Properties of Some Plastics at Low Temperatures. Report 24/R/55. Explosives Research and Development Establishment, Essex, England, November 1955.

24. J. Dyment and H. Ziebland: "The Tensile Properties of Some Plastics at Low Temperatures." Journal of Applied Chemistry (London), Vol 8, 1958, p 203.

25. H. L. Laquer and E. L. Head: Low Temperature Thermal Expansion of Plastics. AECU-2161. Los Alamos Scientific Laboratory, September 1952.

26. F. Nix and D. MacNair: "The Thermal Expansion of Pure Metals: Copper, Gold, Aluminum, Nickel, and Iron." Phys. Rev., Vol 60, 1941, p 597.

27. F. M. Howell: "Low-Temperature Properties and Applications of Aluminum Alloys." Conference on Materials and Design for Low-Temperature Service. Engineer Research and Development Laboratories, Fort Belvoir, Virginia, May 1952, p 253. Also, see Alcoa Research Laboratories Report 9-M-214, November 1953.

28. Data from Armco Steel Corp, Middletown, Ohio, as quoted in Defense Materials Information Center Report 112, Battelle Memorial Institute, Columbus, Ohio, 1959.

29. Investigation of the Influence of Chemistry on Low-Temperature Behavior of Titanium Alloys. Data Bulletin EFE. Titanium Metals Corp of America, May 1962.

30. M. G. Fontana: Investigation of Mechanical Properties and Physical Metallurgy of Aircraft Alloys at Very Low Temperatures. WADC TR 5662 Part II. Ohio State University Research Foundation, October 1948.

31. J. L. Zambrow and M. G. Fontana: "Mechanical Properties, Including Fatigue, of Aircraft Alloys at Very Low Temperatures." Trans. Am. Soc. Metals, Vol 41, 1949, p 480.

32. J. L. Zambrow and M. G. Fontana: "Impact Strength and Hardness of Aircraft Alloys Down to -423°F." Metal Progress, Vol 53, 1948, p 97.

33. M. P. Hanson and H. T. Richards: Smooth and Sharp-Notch Property Variations for Several Heats of Ti-6Al-4V Sheet at Room and Cryogenic Temperatures. NASA TN D-1282. Lewis Research Center, May 1962.

34. Some Properties of Inco Nickel Alloys at Low Temperatures. The International Nickel Co, New York, 1956.

35. Stainless Steel Handbook. Allegheny Ludlum Steel Corp, Pittsburgh, Pa., 1951, p 67.

36. H. L. Johnston and H. E. Brooks: Impact Strength of Various Metals at Temperatures Down to 20° Absolute. Tech. Rep. 264-17. Ohio State University Research Foundation, May 1952.

37. M. P. Hanson et al.: Sharp-Notch Behavior of Some High Strength Sheet Aluminum Alloys and Welded Joints at 75, -320, and -423°F. Spec. Tech. Pub. 287. ASTM, 1960.

38. Union Carbide and Carbon Research Laboratory data, as quoted in Metals Handbook, Am. Soc. Metals, 1948, p 204.

39. C. A. Swenson: "The Compressive Strengths of Some Technical Metals in Compression between 4.2 and 300°K." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 1, 1954, p 251.

40. G. B. Espey et al.: Sharp-Edge-Notch Tensile Characteristics of Several High-Strength Titanium Sheet Alloys at Room and Cryogenic Temperatures. Spec. Tech. Pub. 287. ASTM, 1960.

41. J. L. Christian: Mechanical Properties of High-Strength Sheet Materials at Cryogenic Temperatures. ERR-AN-255. General Dynamics/Astronautics, November 1962.

42. H. E. Brooks and H. L. Johnston: Hardness of Various Metals at Temperatures Down to 20°K. Tech. Rep. 264-20. Ohio State University Research Foundation, May 1952.

43. J. L. Christian: Mechanical Properties of Aluminum Alloys at Cryogenic Temperatures. MRG-190. Convair/Astronautics, December 1962.

44. R. P. Mikesell and R. P. Reed: "The Impact Testing of Various Alloys at Low Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 3, 1957, p 316.

45. R. M. McClintock: "Low Temperature Tensile Properties of Copper and Four Bronzes." ASTM Bulletin, Vol 240, 1959, p 47.

46. J. L. Christian and A. Hurlich: Physical and Mechanical Properties of Pressure Vessel Materials for Application in Cryogenic Environment. ASD-TDR-62-258, Part II. General Dynamics/Astronautics, April 1963.

47. D. E. Furman: "Thermal Expansion Characteristics of Stainless Steels between -300°F and 1000°F." J. Metals, Vol 188, 1950, p 688.

48. Technical data on Allegheny Ludlum alloy A-286. Allegheny-Ludlum Steel Corp, Pittsburgh, Pa., 1952.

49. Haynes Alloy No. 25. Haynes Stellite Co, Kokomo, Ind., 1957.

50. L. P. Rice et al.: The Evaluation of the Effects of Very Low Temperatures on the Properties of Aircraft and Missile Metals. WADD TR 60-254. Battelle Memorial Institute, February 1960.

51. F. R. Schwartzberg and R. D. Keys: Mechanical Properties of 2000 Series Aluminum Alloys at Cryogenic Temperatures. R-61-32. Martin Company, Denver, Colorado, October 1961.

52. E. W. Colbeck and W. E. MacGillivray: "The Mechanical Properties of Metals at Low Temperatures, Part II." Trans. Inst. of Chem. Engrs. (London), Vol 11, 1933, p 107.

53. R. Markovich and F. R. Schwartzberg: Testing Techniques and Evaluation of Materials for Use at Liquid Hydrogen Temperature. Spec. Tech. Pub. 302. ASTM, 1961, p 113.

54. W. D. Jenkins and T. G. Digges: "Effect of Temperature on the Tensile Properties of High-Purity Nickel." J. Research NBS, Vol 48, 1952, p 313.

55. J. H. Hoke et al.: "Mechanical Properties of Stainless Steels at Subzero Temperatures." Metal Progress, Vol 55, 1949, p 643.

56. J. F. Watson and J. L. Christian: The Effect of Cryogenic Temperatures on the Mechanical Properties of High Strength Sheet Alloys (Cold Worked Austenitic Stainless Steels). ERR-AN-003. General Dynamics/Astronautics, May 1960.

57. P. L. Teed: The Properties of Metallic Materials at Low Temperatures. John Wiley and Sons, New York, 1950.

58. R. H. Henke: "Low Temperature Properties of the Austenitic Stainless Steels." Prod. Eng., Vol 20, 1949, p 104.

59. J. F. Watson and J. L. Christian: Low-Temperature Properties of K-Monel, Inconel-X, Rene 41, Haynes 25, and Hastelloy B Sheet Alloys. Paper 61-WA-12. ASME, 1962.

60. H. W. Altman et al., Ohio State University unpublished data, as quoted by H. L. Laquer in Document 3706, Office of Technical Services, US Department of Commerce, 1952.

61. T. S. DeSisto: Automatic Impact Testing to 8°K. Tech. Rep. 112/93. Watertown Arsenal Laboratories, July 1958.

62. T. Rubin et al.: "Coefficients of Thermal Expansion of Solids at Low Temperatures, I. The Thermal Expansion of Copper from 15 to 300°K." J. Am. Chem. Soc., Vol 76, 1954, p 5289.

63. I. Estermann and J. E Zimmerman: "Heat Conduction in Alloys at Low Temperatures." J. Appl. Phys., Vol 23, 1952, p 578.

64. J. C. Campbell and L. P. Rice: Properties of the Precipitation-Hardening Stainless Steels and Low-Alloy High-Strength Steels at Very Low Temperatures. Spec Tech. Pub. 287. ASTM, 1960, p. 158.

65. T. N. Armstrong et al.: "Properties Affecting Suitability of 9 Percent Nickel Steel for Low-Temperature Service." Welding J. Research Supplement, February 1959.

66. J. C. Hamaker Jr., and E. J. Vater: Carbon: Strength Relationships in 5 Percent Chrominum Ultra-High Strength Steels. Preprint 80. ASTM, 1960.

67. G. Sachs and J. G. Sessler: Effect of Stress Concentration on Tensile Strength of Titanium and Steel Alloy Sheet at Various Temperatures. Spec. Tech. Pub. 287. ASTM, 1960, p 122.

69. C. F. Lucks and H. W. Deem: Thermal Properties of Thirteen Metals. Spec. Tech. Pub. 227. ASTM, 1958, p 1.

70. H. W. Altman et al.: Coefficients of Thermal Expansion of Solids at Low Temperatures, Part II. Tech. Rep. 264-19. Ohio State University Research Foundation. As quoted by R. J. Corruccini and J. J. Gniewek in NBS Monograph 29, 1961.

71. R. W. Powers et al.: The Thermal Conductivity of Metals and Alloys at Low Temperatures, Part II. Tech. Rep. 264-6. Ohio State University Research Foundation, 1951. As quoted by R. L. Powell and W. A. Blanpied in NBS Circular 556, 1954.

72. R. L. Powell et al.: "Low Temperature Transport Properties of Commercial Metals and Alloys, II." J. App. Phys., Vol 31, 1960, p 496.

73. H. W. Altman et al.: Coefficient of Thermal Expansion of Solids, Part III. Tech. Rep. 264-27. Ohio State University Research Foundation, 1954. As quoted by R. J. Corruccini and J. J. Gniewek in NBS Monograph 29, 1961.

74. R. W. Powers et al.: The Thermal Conductivity of Metals and Alloys at Low Temperatures, Part III. Tech. Rep. 264-8. Ohio State University Research Foundation, 1951. As quoted by R. L. Powell and W. A. Blanpied in NBS Circular 556, 1954.

75. E. H. Schmidt: "Low Temperature Impact of Annealed and Sensitized 18-8." Metal Progress, November 1948, p 698.

76. C. F. Hickey, Jr.: Mechanical Properties of Titanium and Aluminum Alloys at Cryogenic Temperatures. Paper presented at Annual ASTM Meeting, New York, June 1962.

77. C. H. Curll and G. M. Orner: Correlation of Selected Subsize Charpy Bars vs the Standard Charpy Bar. Tech. Rep. 112/91. Watertown Arsenal Laboratories, 1958.

78. H. J. French: "Some Aspects of Hardenable Alloy Steels." Transactions of the American Institute of Metal Engineers, Vol 206, 1956, p 770.

79. C. J. Guntner and R. P. Reed: "Mechanical Properties of Four Austenitic Stainless Steels at Temperatures Down to 20°K." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 6, 1961.

80. R. K. Kirby: "Thermal Expansion of Polytetrafluoroethylene (Teflon) from -190° to 300°C." J. Research NBS, Vol 57, 1956, p 91.

81. J. H. Belton et al.: Materials for Use at Liquid Hydrogen Temperature. Spec. Tech. Pub. 287. ASTM, 1960, p 108.

82. H. W. Altman et al.: Coefficients of Thermal Expansion of Solids at Low Temperatures, Part IV. Tech. Rep. 264-28. Ohio State University Research Foundation. As quoted by R. J. Corruccini and J. J. Gniewek in NBS Monograph 29, 1961.

83. F. R. Schwartzberg and R. D. Keys: "Mechanical Properties of an Alpha Titanium Alloy at Cryogenic Temperatures." Proceedings of ASTM, Vol 62, 1963, p 816.

84. J. L. Christian and J. F. Watson: Mechanical Properties of Several 2000 and 6000 Series Aluminum Alloys at Cryogenic Temperatures. General Dynamics/Astronautics. Paper presented at Cryogenic Engineering Conference, Los Angeles, California, 1962.

85. J. L. Christian and J. F. Watson: "Properties of 7000 Series Aluminum Alloys at Cryogenic Temperatures." Advances in Cryogenic Engineering, Vol 6, 1960, p 604.

86. C. A. Swenson: "Mechanical Properties of Teflon at Low Temperatures." Rev. Sci. Instr., Vol 25, 1959, p 134.

87. B. B. Betty and W. A. Mudge: "Some Engineering Properties of Nickel and High-Nickel Alloys." Mech. Eng., Vol 67, 1945, p 123.

88. T. Broom: "The Effect of Temperature of Deformation on the Electrical Resistivity of Cold-Worked Metals and Alloys." Proc. Phys. Soc. (London), Vol 65, 1952, p 871.

89. C. J. Smithells: Metals Reference Book. Interscience Publishers, New York, 1949.

90. P. L. Teed: "Aircraft Metallic Materials under Low Temperature Conditions." J. Roy. Aeronaut. Soc., Vol 55, February 1951, p 61.

91. D. J. McAdam, Jr. et al.: "Effects of Combined Stresses and Low Temperatures on the Mechanical Properties of Some Nonferrous Metals." Am. Soc. Metals, Vol 37, 1946, p 497.

92. R. W. Powers et al.: The Thermal Conductivity of Metals and Alloys at Low Temperatures, Part I. Tech. Rep. 264-5. Ohio State University Research Foundation, 1951. As quoted by R. L. Powell and N. A. Blanpied in NBS Circular 556, 1954.

93. G. L. Richards and R. M. Brick: "Technical Properties of Beryllium Copper at Subzero Temperatures." J. Metals, Vol 6, 1954, p 574.

94. C. H. Lees: "The Effects of Temperature and Pressure on the Thermal Conductivities of Solids, Part V." Phil. Trans. Royal Society (London), Series A208, 1908. As quoted in NBS Circular 556, 1954.

95. E. W. Colbeck et al.: "The Mechanical Properties of Some Austenitic Stainless Steels at Low Temperatures." Trans. Inst. Chem. Engrs. (London), Vol 11, 1933, p 89.

96. D. J. McAdam and R. W. Mebs: "The Technical Cohesive Strength and Other Mechanical Properties of Metals at Low Temperatures." Proc. ASTM, Vol 43, 1943, p 661.

97. G. W. Geil and N. L. Carwile: Tensile Properties of Copper, Nickel, and Some Copper-Nickel Alloys at Low Temperatures. Circular 520. National Bureau of Standards, 1952, p 67.

98. Materials Property Manual and Summary Report, Contract No. AF33(600)-28469. AL2604. North American Aviation, Missile Development Division, Downey, Calif., 1957.

99. Engineering Properties of "S" Monel. International Nickel Co, New York, 1957.

100. J. G. Kaufman, et al.: "Tensile Properties and Notch Toughness of Aluminum Alloys at -452°F in Liquid Helium." Advances in Cryogenic Engineering. Plenum Press, New York, Vol 13, 1967.

101. J. W. Coursen: Mechanical Properties and Fracture Characteristics of Some X2021-T81 and X7007-T6E136 Sheet and Plate. Report No. 9-67-19. Aluminum Company of America, New Kensington, Pennsylvania, August 21, 1967.

102. G. B. Espey et al.: Some Factors Influencing the Fracture Toughness of Sheet Alloys for Use in Lightweight Cryogenic Tankage. Spec. Tech. Pub. 302. ASTM, 1961, p 140 thru 165.

103. Mechanical-Property Data 2021 Aluminum Plate (-T8E31). AF33 (615)-2494. Battelle Memorial Instritute, June 1967.

104. C. V. Lovoy: Low-Temperature Mechanical Properties of Inconel-X and Its Weldments. IN-P&VE-M-62-5. Marshall Space Flight Center, 24 July 1962.

105. P. J. Soltis: Evaluation of Crucible Steel Company of America B-120VCA Titanium Alloy. NAMC-AML-AE 1108. Aeronautical Materials Laboratories, Naval Air Material Center, December 1959.

106. H. W. Gillett: Impact Resistance and Tensile Properties of Metals at Subatmospheric Temperatures. Spec. Tech. Pub. 47. ASTM, 1941.

107. J. L. Christian et al.: Mechanical Properties of Titanium - 5Al-2.5Sn Alloy at Room and Cryogenic Temperatures. Paper to be published by ASTM.

108. J. J. M. Beenaker and C. A. Swenson: "Total Thermal Contractions of Some Technical Metals to 4.2°K." Rev. Sci. Instr., Vol 26, 1955, p 1204. As quoted by R. J. Corruccini and J. J. Gniewek in NBS Monograph 29, 1961.

109. R. D. McCammon and H. M. Rosenberg: "The Fatigue and Ultimate Tensile Strengths of Metals between 4.2 and 293°K." Proc. Roy. Soc. (London), Vol 242, 1957, p 203.

110. R. K. MacCrone et al.: "The Fatigue of Metals at 1.7°K." Phil. Mag., Vol 4, 1959, p 267.

111. M. P. Hanson: Smooth and Sharp-Notch Tensile Properties of Cold-Reduced AISI 301 and 304L Stainless Steel Sheet at 75, -320, and -423°F. NASA TN D-592. Lewis Research Center, February 1961.

112. R. E. Bathgate: Fatigue Strength of A-286 Alloy Steel at 78°K. UCRL-70477. Lawrence Radiation Laboratory, Livermore, California.

113. V. N. Krivobok: Properties of Austenitic Stainless Steels at Low Temperatures. Circular 520. National Bureau of Standards, 1952, p 112.

114. N. O. Brink: Determination of the Performance of Plastic Laminates under Cryogenic Temperatures. ASD-TDR-62-794. Narmco Research and Development, February 1963.

115. J. F. Watson and J. L. Christian: Mechanical Properties of High Strength 301 Stainless Steel Sheet at 70, -320, and -423°F in the Base Metal and Welded Joint Configuration. Spec. Tech. Pub. 287. ASTM, 1960, p 136 thru 149.

116. C. V. Lovoy: Low-Temperature Mechanical Properties of X2020-T6 and 2219-T6 Aluminum Sheet Alloys. IN-P&VE-M-62-3. Marshall Space Flight Center, May 1962.

117. W. R. Morgan: Mechanical Properties of 2219-T87 Alloy Plate at Room and Cryogenic Temperatures. IN-P&VE-M-62-9. Marshall Space Flight Center, October 1962.

118. W. R. Morgan: Low-Temperature Mechanical Properties of K-Monel Alloy and Its Weldments. IN-P&VE-M-62-8. Marshall Space Flight Center, 28 August 1962.

119. W. R. Morgan: Low-Temperature Mechanical Properties of A-286 and Its Weldments. IN-P&VE-M-62-4. Marshall Space Flight Center, 28 May 1962.

120. J. Nunes and F. R. Larson: "Low-Temperature Tensile-Hardness Correlations for SAE 4340 Steel." ASTM Bulletin, No. 249, October 1960, p 25.

121. A. W. Brisbane: The Investigation of the Effects of Loading Rate and Stress Concentration Factors of the Notch Properties of Three Sheet Alloys at Subzero Temperatures. ASD-TDR-62-930. Wright-Patterson Air Force Base, Ohio, March 1963.

122. L. P. Rice et al.: "The Tensile-Property Evaluation of One 5000-Series Aluminum Alloy at the Temperature of Liquid Helium." Advances in Cryogenic Engineering. Plenum Press, New York, Vol 8, 1962, p 671.

123. P. C. Miller: Low-Temperature Mechanical Properties of Several Aluminum Alloys and Their Weldments. MTP-S&M-M-61-16. Marshall Space Flight Center, October 1961.

124. J. L. Christian: Evaluation of Materials and Test Methods at Cryogenic Temperatures. ERR-AN-400. General Dynamics/Astronautics, 10 December 1963.

125. J. L. Christian et al.: Physical and Mechanical Properties of Pressure Vessel Materials for Application in Cryogenic Environment. GD/A 63-0818-3. Quarterly Report on Contract AF33(657)-11289, Phase II, General Dynamics/Astronautics, May 1964.

126. Effects of Low-Temperatures on Structural Metals. NASA SP-5012. Marshall Space Flight Center, December 1964.

127. W. R. Morgan: Low-Temperature Mechanical Properties of Aluminum Alloy Plate X7002-T6 and Its Weldments. IN-P&VE-M-63-2. Marshall Space Flight Center, 9 January 1963.

128. W. A. Anderson et al.: "Notch Sensitivity of Aluminum-Zinc-Magnesium Alloys at Cryogenic Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 9, 1963, p 104.

129. J. L. Christian et al.: "Structural Alloys for Cryogenic Service." Metals Progress, March 1949, p 101.

130. T. S. DeSisto: Low Temperature Mechanical Properties of Base and Weld Deposits of Selected Austenitic Stainless Steels. AMRA TR 63-08, U.S. Army Materials Research Agency, July 1963.

131. J. E. Chafey and J. L. Christian: Development of High Strength Sheet Alloys for Cryogenic Applications. ERR-AN-257, General Dynamics/Astronautics, December 1962.

132. "Subzero Tensile Properties of Ti-3Al-2.5 Sheet." Technical Data from Bridgeport Brass Company, December 1963.

133. W. Weleff et al.: "Cryogenic Tensile Properties of Selected Aerospace Materials." Advance in Cryogenic Engineering, Plenum Press, New York, Vol 10, 1965, Sec. A-L p 14.

134. "Reynolds Aluminum in Cryogenics," Bulletin, Reynolds Metals Company, Richmond, Virginia.

135. "Cryogenic Applications of Alcoa Aluminum," Bulletin, Aluminum Company of America.

136. J. F. Watson and J. L. Christian: The Effects of Cryogenic Temperatures on the Mechanical Properties of High Strength Sheet Alloys. (Nonferrous Alloys), ERR-AN-002, General Dynamics/Astronautics, April 1960.

137. D. L. Corn: "Cryogenic Properties of 18Ni-9Co-5Mo and 18Ni-7Co-5Mo Maraging Steel Sheet." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 12, 1966. p 532.

138. P. L. Mehr et al.: Alcoa Alloy 7075-T73. Green Letter. Aluminum Company of America, August, 1965.

139. F. W. DeMoney: "Effect of Aging on the Tensile Properties of Alloy 7039 GTA Welds at Low Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 12, 1966, p 500.

140. C. R. Denaburg: Low Temperature Mechanical Properties of Aluminum Alloy 2219-T87, 0.040-Inch Thick Sheet through 5.000-Inch Thick Plate. TM X 53332. Marshall Space Flight Center, NASA, September 1965.

141. R. D. Olleman and G. C. Wolfer: The Tensile and Impact Properties of Plate and Welds of Aluminum Alloy 5083-H113 between 75°F and -320°F. Bulletin, Kaiser Aluminum and Chemical Corporation.

142. T. S. Desisto and F. L. Carr: Low Temperature Mechanical Properties of 300 Series Stainless Steel and Titanium. WAL MS-22. Watertown Arsenal Laboratories, Watertown, Massachusetts, May 1961.

143. C. O. Malin: Low-Temperature Properties of Armco 21-6-9 Alloy. MPR 3-251-336, Internal Letter, North American Aviation Inc., October 1963.

144. E. B. Kula, et al.: Plastic Behavior of Metals at Cryogenic Temperatures. AMRA TR 65-32. Watertown Arsenal Laboratories, Watertown, Massachusetts, December 1965.

145. C. M. Carman, et al.: Plane Strain Fracture Toughness of 2219-T87 Aluminum Alloy at Room and Cryogenic Temperatures. NASA CR-54297, R-1821. Frankford Arsenal, Philadelphia, Pa., August 1966.

146. S. W. McClaren, et al.: Biaxial Strength Characteristics of Selected Alloys in a Cryogenic Environment. Report 2-53420/CR-2279. LTV Aerospace Corporation, May 1966.

147. C. E. Cataldo: Weldability Studies of 5456-H343 and 2219-T87 Aluminum Alloy Plates. IN-P&VE-M-62-2. Marshall Space Flight Center, April 1962.

148. T. L. Sullivan: Unaxial and Biaxial Fracture Toughness of Extra-Low-Interstitial 5Aℓ-2.5Sn Titanium Alloy Sheet at 20°K. NASA TN-D-4016. Lewis Research Center, Cleveland, Ohio, June 1967.

149. T. S. Desisto: The True-Stress True-Strain Properties of of Titanium and Titanium Alloys as a Function of Temperature and Strain Rate. WAL TR 405.2/4. Watertown Arsenal, Watertown, Massachusetts, March 1960.

150. J. F. Watson and J. L. Christian: "Cryostat and Accessories for Tension Testing at -423°F." Materials Research and Standards. Vol 1, No. 2, February 1961.

151. R. M. McClintock and K. A. Warren: "Tensile Cryostat for the Temperature Range 4° to 300°K." Materials Research and Standards. Vol 1, No. 2, February 1961.

152. R. D. Keys: "A Multiple Tensile Specimen Test Device for Use in Liquid Hydrogen." Advances in Cryogenic Engineering. Plenum Press, New York, Vol 7, 1962, p 455.

153. R. P. Reed: "A Cryostat for Tensile Tests in the Temperature Range 300° to 4°K." Advances in Cryogenic Engineering. Plenum Press, New York, Vol 7, 1962, p 455.

154. E. T. Wessel: "Apparatus for Tensile Testing in the Temperature Range of 4.2° to 300°K." Advances in Cryogenic Engineering. Plenum Press, New York, Vol 1, 1954, p 242.

155. W. R. Lucas and C. E. Cataldo: "Some Low Temperature Properties of Aluminum-Alloy Weldments." Spec Tech Pub 287. ASTM, 1960, p 23 - 36.

156. T. F. Kiefer et al.: "Charpy Impact Testing at 20°K." Advances in Cryogenic Engineering. Plenum Press, New York, Vol 10 Sec. A-L, p. 56, 1965.

157. L. L. France et al.: "Apparatus for Hardness Testing at Low Temperatures." Materials Research and Standards, Vol 1, No. 3, March 1961, p 192.

158. R. P. Mikesell and R. M. McClintock: "A Method of Measuring Shear Modulus from -423° to 70°F." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 7, 1961, p 509.

159. P. Hidnert and W. Souder: "Thermal Expansion of Solids." NBS Circular No. 486, 1950.

161. National Bureau of Standards, Cryogenic Engineering Laboratories, Boulder, Colorado (unpublished information).

162. G. V. Aseff et al.: "Tensile, Compression and Shear Loop for Irradiation Testing at Cryogenic Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 8, 1962, p 624.

163. R. M. McClintock: "Strain Gage Calibration Device for Extreme Temperatures." Review of Scientific Instruments, Vol 30, No. 8, August 1959, p 715.

164. P. T. Chiarito: "Strain Measurement at Cryogenic Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 7, 1961, p 433.

165. R. D. Keys, Martin Company, Denver, Colorado (unpublished information).

166. A. Kaufman: Performance of Electrical-Resistance Strain Gages at Cryogenic Temperatures. NASA TN D 1663. Lewis Research Center, March 1963.

167. R. H. Kemp: "Characteristics and Application of Foil Strain Gages at -423°F." Published in the Proceedings of The Western Regional Strain Gage Conference, June 1964.

168. R. D. Keys and F. R. Schwartzberg: "Techniques for Axial Fatigue Testing of Sheet Materials Down to -423°F." Materials Research and Standards, Vol 4, No. 5, p 222, May 1964.

169. J. F. Watson et al.: A Study of the Effects of Nuclear Radiation on High-Strength Aerospace Vehicle Materials at the Boiling Point of Hydrogen (-423°F). ERR-AN-085. General Dynamics/Astronautics, September 1961.

170. W. Weleff et al.: "Shear Strength of Several Alloys at Liquid Hydrogen Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 10, Sec A-L, p 50, 1965.

171. L. W. Toth and A. H. Kariotis: "An Assessment of Test Specimens and Test Techniques Useful to the Evaluation of Structural Reinforced Plastics Materials at Cryogenic Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 10, Sec A-L, p 126, 1965.

172. T. F. Kiefer et al.: Determination of Low Temperature Fatigue Properties of Structural Metal Alloys, Final Report. Martin Company, Denver, Colorado, October 1965, Prepared under NASA Contract NAS8-11300.

173. P. C. Miller: Low Temperature Mechanical Properties of Rene' 41 Alloy and Its Weldments. IN-P & VE-M-62-6, Marshall Space Flight Center, NASA, July 1962.

174. Beech Aircraft Co., Boulder, Colorado. (Unpublished data)

175. C. M. Carman et al.: Plane Strain Fracture Toughness and Mechanical Properties of 2219-T87 Aluminum Alloy at Room and Cryogenic Temperatures. NASA CR-54297, Frankford Arsenal Report

176. The Aluminum Data Book. Reynolds Metals Company, p 46, 1961.

177. Data obtained by Douglas Aircraft, Santa Monica, California, under NASA Contract NAS3-4192.

178. H. Y. Hunsicker and J. H. Hess: "New Weldable High Strength Aluminum Alloys for Cryogenic Service." Advances in Cryogenic Engineering. Plenum Press, New York. Vol 11, p 423, 1966.

179. J. L. Christian: Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment. ASD-TDR-62-258, Part III, General Dynamics/Astronautics, December 1964.

180. C. M. Carman et al.: Plane Strain Fracture Toughness and Mechanical Properties of 5Al-2.5Sn Titanium Alloy at Room and Cryogenic Temperatures. NASA CR 54296, Frankford Arsenal Report

181. C. M. Carman and D. F. Armiento: "Plane-Strain Fracture Toughness of High-Strength Aluminum Alloys." Journal of Basic Engineering, ASME, p 904, December 1965.

182. J. G. Kaufman and E. W. Johnson: "Notch Sensitivity of Aluminum Alloy Sheet and Plate at -320°F Based Upon Notch-Yield Ratio." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 8, 1962.

183. The Boeing Company, Seattle, Washington. (Unpublished Data)

184. C. F. Tiffany and P. M. Lorenz: An Investigation of Low-Cycle Fatigue Failures Using Applied Fracture Mechanics. ML-TDR-64-53, The Boeing Company, May 1964.

185. Martin Company, Denver, Colorado. (Unpublished data)

186. P. M. Lorenz: Fracture Toughness and Subcritical Flaw Growth Characteristics of Saturn SI-C Tankage Materials. Boeing Report No. D2-22802, Prepared under NASA Contract NAS8-5608, April 1964.

187. "18% Ni Maraging Steel" Data Sheet. United States Steel Corporation, September 1964.

188. F. W. de Money and G. C. Wolfer: "The Fatigue Properties of Aluminum Alloy 5083-H113 Plate and Butt Weldments at 75° and -300°F." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 6, 1960.

189. L. P. Rice et al.: "Tensile Behavior of Parent-Metal and Welded 5000-Series Aluminum Alloy Plate at Room and Cryogenic Temperatures." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 7, 1961.

190. W. J. Hall et al.: "Thermal Conductivities of Common Commercial Aluminum Alloys." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 3, 1957.

191. R. L. Powell and D. O. Coffin: "Low-Temperature Thermal Conductivity of Free-Machining Copper." Review of Scientific Instruments, Vol 26, No. 5, p 516, May 1955.

192. C. R. Denaburg: Low-Temperature Mechanical Properties of 8Al-1Mo-1V Titanium Alloy and Composite Weldments. NASA TM X-53178, Marshall Space Flight Center, December 1964.

193. J. G. Kaufman and E. W. Johnson: "New Data from Alcoa Research Laboratories on Aluminum in Cryogenic Applications." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 9, 1963.

194. F. W. de Money: "Performance of a New Cryogenic Alloy, 7039." Advances in Cryogenic Engineering, Plenum Press, New York, Vol 9, 1963.

195. "Weldable/Heat-Treatable Aluminum Alloy 7039." Bulletin, Kaiser Aluminum and Chemical Corporation, June 1965.

196. C. F. Tiffany et al.: Investigation of Plane-Strain Flaw Growth in Thick-Walled Tanks. NASA CR 54837, Boeing Company Report D2-20478-1, February 1966.

197. T. S. DeSisto and C. F. Hickey, Jr.: Low-Temperature Mechanical Properties and Fracture Toughness of Ti 6Aℓ-6V-2Sn. AMRA TR 65-17. Watertown Arsenal, Watertown, Massachusetts, July 1965.

198. N. H. Fahey: Ultrasonic Determination of Elastic Constants at Room and Low Temperatures. WAL TR 118.1/1. Watertown Arsenal, Watertown, Massachusetts, April 1960.

199. W. E. Witzell: Fracture Data for Materials at Cryogenic Temperatures. AFML-TR-67-257. Wright-Patterson Air Force Base, Ohio, November 1967.

200. L. W. Toth et al.: Program for the Evaluation of Structural Reinforced Plastic Materials at Cryogenic Temperatures, Final Report. CR-80061. George C. Marshall Space Flight Center, National Aeronautics and Space Administration, August 1966.

201. R. P. Reed and R. P. Mikesell: "Low-Temperature (295 to 4°K) Mechanical Properties of Selected Copper Alloys." Journal of Materials. Vol 2, No. 2, June 1967, p 370.

202. M. P. Hanson et al: Preliminary Investigation of Filament-Wound Glass-Reinforced Plastics and Liners for Cryogenic Pressure Vessels. NASA TN D-2741. Lewis Research Center, Cleveland, Ohio, March 1965.

203. J. F. Haskins et al.: Thermophysical Properties of Plastic Materials and Composites to Liquid Hydrogen Temperature (-423°F). Parts I, II and III, ML-TDR-64-33. General Dynamics/Astronautics, August 1965.

204. General Dynamics, Convair Division, San Diego, California. (Unpublished Data), May 1967.

205. F. T. Inouye et al.: Application of Alloy 718 in M-1 Engine Components. NASA CR-788. Aerojet-General Corporation, for Lewis Research Center, June 1967.

206. C. O. Malin and E. H. Schmidt: Tensile and Fatigue Properties of Alloy 718 at Cryogenic Temperatures. Technical Report C7-23.3. (Presented at the National Metal Congress, ASM) October 1967.

207. Y. S. Touloukian et al.: Thermophysical Properties Research Center Data Book, Vol 1, Ch. 1, June, 1966.

208. R. L. Powell, W. J. Hall, and H. M. Roder: "Low-Temperature Transport Properties of Commercial Metals and Alloys. II. Aluminums." Journal of Applied Physics, Vol 31, No. 3, p 496-503, March, 1960.

209. J. G. Hust, D. H. Weitzel, and R. L. Powell: Thermal Conductivity of Aerospace Alloys at Cryogenic Temperatures. Paper presented at the 7th Conference of Thermal Conductivity, National Bureau of Standards, Gaithersburg, Md., November 13-16, 1967.

210. J. G. Hust: (Unpublished data), National Bureau of Standards, Institute for Materials Research, Cryogenics Division, Boulder, Colorado.